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REVIEW OF COMPLIANT COATING RESEARCH OF M. O. KRAMER.(U)
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REVIEW OF COMPLIANT COATING
RESEARCH OF M.O. KRAMER

ROGER P. JOHNSON

FINAL REPORT

N00014-80-C-0955

OCTOBER 17, 1980

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER RPJA-TR-0955-001	2. GOVT ACCESSION NO. AD-A094044	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REVIEW OF COMPLIANT COATING RESEARCH OF M.O. KRAMER		5. ~~TYPE OF REPORT & PERIOD~~ COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Roger P. Johnson		8. CONTRACT OR GRANT NUMBER(s) N00014-80-C-0955
9. PERFORMING ORGANIZATION NAME AND ADDRESS R P J Associates, Inc. P.O. Box 2101 Palos Verdes Peninsula, CA 90274		10. PROGRAM ELEMENT, PROJECT, TASK ~~AREA & WORK UNIT~~ NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Department of the Navy Arlington, VA 22217		12. REPORT DATE October 17, 1980
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This technical report summarizes the 19-year history of experimental research on compliant coatings performed by Dr. Max O. Kramer. In addition to the drag reduction in the transitional flow region, the several test techniques, the various bodies of revolution, and the compliant coating designs are described in detail.

PREFACE

Renewed interest in the potential for skin friction drag reduction in liquid media prompted a thorough review of the experimental results, circa 1957-1975, of Dr. Max O. Kramer with compliant coatings in the transition region. Kramer's results have not previously been assembled and portions had not been formally published.

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SUMMARY

The experimental research program on compliant coatings to extend the laminar flow region, as conducted by Dr. Max O. Kramer during the period 1957-1975 has been assembled from various sources in complete form.

The initial four years of research were supported by the Office of Naval Research and this was followed by five years supported by personal consulting. The concluding period was supported by personal funds of the investigator.

The experimental test techniques are described for the lanyard-towed and strut-mounted test bodies and for the positive-buoyancy, submerged-release "pop-up" bodies. The coating designs evolved rapidly into three-layer coatings: (1), with replaceable high viscosity fluids in the stubbed or ribbed lower layer; (2), with replaceable middle layers of various physical properties; and (3), with very thin, very high resiliancy top layer.

The experimental data are assembled, as presented by the investigator without reduction or analysis.

CONTENTS

SYMBOLS

ASNE	American Society of Naval Engineers
A_w	wetted surface area, m^2
B	buoyancy, kg
BL	boundary layer
CALTECH	California Institute of Technology, Pasadena, CA
C_d	average drag coefficient of test body, based upon A_w
cm	centimeter
C_r	resistance coefficient including friction, roughness, and form contributions
d	diameter
DGLR	Deutschen Gesellschaft fur Luft- und Raum Fahrt
E	modulus of elasticity, Young's modulus, psi/in
f	frequency, Hz, or kHz
$\overline{FR}$	fineness ratio, ℓ/d
g	gravitational constant, 9.8064 m/sec^2
gm	gram
Hz	Hertz
JPL	Jet Propulsion Laboratory, Pasadena, CA
kg	kilogram
ℓ	length, cm
LTV	potting compound designation by General Electric
M	tensile modulus for 100 per cent elongation of rubber specimen, psi
m	meter
m/sec	meters/second

MOK	Dr. Max O. Kramer
NBS	National Bureau of Standards, Gaithersburg, MD
pci	pounds per cubic inch, lbs/in^2 per in
R_e	Reynolds number, $\frac{\rho v \ell}{\mu}$, based on test specimen length
RR10	elastic paint designation by Floquil Paint Company
δt	ascent time for buoyant body, seconds
V	volume, $meters^3$
υ	velocity, m/sec
υ_t	terminal velocity
W	weight, kg
λ	wave length, cm
ρ	density of salt water, 1.02813 gm/cm^3 at 0^oC, 1 atmosphere, salinity 35 per mille
$\frac{\rho}{g}$	mass density, $gmsec^2/cm^4$
μ	viscosity gmsec/cm^2
ν	kinematic viscosity, $\frac{\mu}{\rho}$ cm^2/sec

1 INTRODUCTION

1. INTRODUCTION

The thirty year interest of Dr. Max O. Kramer in laminar flow extension into the transition region of boundary layer flow was inspired by observation of Dolphins swimming about a ship on which he crossed the Atlantic Ocean in 1946, as noted in Figure 1-1. This was followed by a period of reading, calculating, and speculating about the reasons for the observed high speed of the dolphin mammal. A microscopic examination of the multiple layered dolphin skin, which he had obtained from a marine biologist at Marineland of the Pacific, influenced Kramer's attempts to design compliant coatings.

Dr. Kramer joined Coleman Engineering of Torrance, California and served as Director of Research from 1952 to 1956, as noted on Figure 1-2. The need for specialized knowledge in rubber compounding and bonding lead to a joint venture with U.S. Rubber Company of Wayne, New Jersey. For this joint venture, Coleman-Kramer, Inc., was established in 1957 to separate the research program. Dr. Kramer served as Vice President and Director of Research through December 1960, when all work was terminated. Support by the Office of Naval Research (ONR) during this four year period was through U.S. Rubber as prime contractor, with Coleman-Kramer as subcontractor. Apparently there were jurisdictional as well as personality differences, magnified by the 2500 mile separation. The so-called "stubbed coating" was used during the 1957-1960 period and is apparent in the U.S. Rubber "Lamiflo" trademark.

Starting in 1961, Dr. Kramer began a period of personal consulting and U.S. Rubber continued rubber coating design testing and development, partially supported by ONR. Dr. Kramer consulted on a part-time basis for the (then) Hydrocraft Group of the (then) Aero-Astronautics Department of The RAND Corporation from 1961-1966. The longitudinally-ribbed (lower layer) coating was used exclusively during this time period. All the suboptimizations of high viscosity fluids in the lower layer were repeated and new middle layers were optimized both as to physical properties and thickness.

- KRAMER FASCINATED BY DOLPHIN SPEED SINCE 1946
- REFERENCE GATHERING AND DOLPHIN SKIN RESEARCH, 1946-1956 EXCLUDED
- KRAMER INFERRED LARGE EXTENT OF LAMINAR FLOW AND DESIGNED TESTS FOR SAME
- KRAMER CONSULTED FOR RAND 1961-1966: HYDROCRAFT GROUP OF RPJ
- REVIEW BASED UPON RPJ HOLDINGS:
  - 3 ASNE ARTICLES
  - 2 RAND RESEARCH MEMORANDUMS
  - 7 RAND INTERNAL DOCUMENTS
  - 1 DAVIDSON LABORATORY LETTER REPORT
  - 7 UNPUBLISHED KRAMER DOCUMENTS
  - 1 DEUTSCHEN GESELLSCHAFT FUR LUFT-UND-RAUMFARHT

FIGURE 1-1 BACKGROUND NOTES

- DIRECTOR OF RESEARCH AT COLEMAN ENGINEERING 1952-1956
- VICE PRESIDENT OF COLEMAN-KRAMER 1956-1960
- CHIEF OF EXPERIMENTAL TESTS FOR JOINT VENTURE 1957-1960
  - LAMIFLO TRADEMARK   MATERIALS FROM US RUBBER   ONR FUNDED
- KRAMER BEDRIDDEN, NOT INVOLVED IN REVIEW
  - MINOR STROKES; SPEECH IMPEDIMENT ONLY
  - HIPSOCKET REPLACEMENT; RECOVERING
- WIFE AND SON FRIENDLY TO RPJ TELECONS
  - NO SUPPLEMENTAL DATA FOUND YET
  - INFORMED OF POSSIBLE FUTURE CONSULTING ON TURBULENT FLOW
  - LOCAL AREA VISITS LATER; 30 MILES DISTANT

FIGURE 1-2 M.O. KRAMER 1952 - 1980

The third major phase of compliant coating design began in 1966 with a search for a homogeneous bottom layer material with physical properties to match those of the combined ribbed coating and the optimized high viscosity fluid filler.

The following sections will treat separately: (Section 2), the evolution of the testing techniques, including the test bodies; (Section 3), the changing coating designs; (Section 4), the reported experimental results from a 19-year period of testing; and (Section 5), an overall evaluation. Appendices A-C will present a brief biography of Dr. Kramer, challenges raised by other investigators, and supplementary information.

2 TECHNIQUES

2. TEST TECHNIQUES

GENERAL

Four major factors directed the major decisions of M.O. Kramer's lengthy period of experimental research on compliant coatings. First, the objective was to extend the region of laminar flow into the transition region and that required very low ambient turbulence. Water tunnels and towing tanks did not operate at such low levels, so attention was directed to testing in estuaries and later the open ocean. The Garfield Thomas Memorial water tunnel at Penn State first achieved 0.03 per cent turbulence in 1966. Second, the transition Reynolds number range $5 \leq R_e x 10^{-6} \leq 20$ with $\ell = 0$ (45" or 114.3CM) requires high water speeds, i.e.,

$$15.12 \leq \nu \leq 60.49 \text{ ft/sec}$$

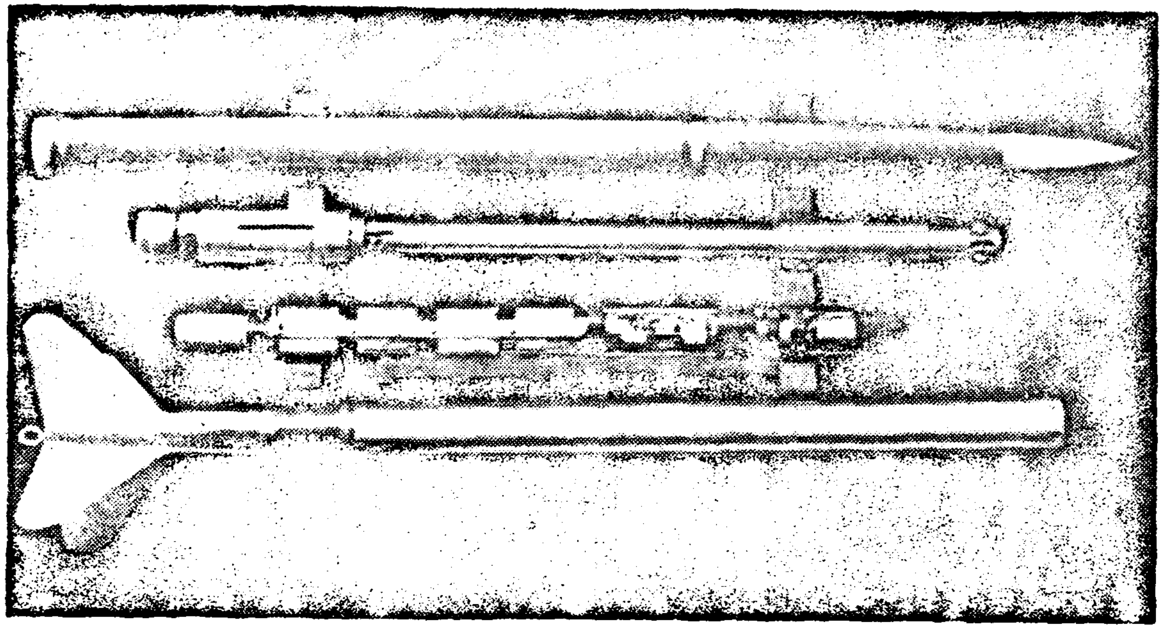
$$8.95 \leq \nu \leq 35.82 \text{ knot}$$

$$4.61 \leq \nu \leq 18.44 \text{ m/sec}$$

Third, many tests would be required with frequent changes of models to include the sub-optimizations of various parameters. Without an adequate theoretical basis, the research would be guided by the empirical results. Fourth, with many tests required to survey a new field and with very limited support in prospect, a low unit cost of each test would be required, even at some loss of accuracy.

TOWED BODIES

The basic body used for towing tests over a period of nine years was 6.35cm in diameter and 243.8cm in overall length. This was comprised of a 113.0cm afterbody which contained the telemetery equipment. These are the lower two components shown on Figure 2-1. The midbody 16.5cm portion contained the strain-gauge and served as a base for the towing attachment and for the sting which supported the cylindrical and ogival forebody on ball bearings. This is shown next to the top on Figure 2-1. The 67.3cm cylindrical test section was connected to the 47.0cm forebody by a threaded joint. At various times, 30.5 and 61.0cm lengths of interchangeable cylindrical sections were recessed



COATED CYLINDER AND COATED FOREBODY AT TOP

MIDBODY WITH STRAIN-GAGES, TOW CABLE CONNECTOR AND STING MOUNT

TELEMETERING UNIT FOR INSERTION IN AFTERBODY

AFTERBODY AND STABILIZING FINS

FIGURE 2-1 DISASSEMBLED 6.35CM TOWED BODY

(machined down) to accommodate coatings of several thicknesses. Similarly, some of the 47.0cm ogival forebodies were prepared to accept 30.5cm lengths of coatings on the rear two-thirds, as shown on Figure 2-2. The forebody coordinates are given by Table 2-1. For some tests with a rigid forebody, a shorter version of 20.3cm length was prepared. The body components were machined from nylon bars and tubes. The overall weight of the assembled body was approximately 22.7kg. The ordinates of the 47.0cm ogive forebody are given by Table 2-1.

The gap between the cylindrical test section and the midbody, strain-gauge section was 0.08cm or less than used on "static sondes" (as on aircraft pitot tubes for static pressure function). This accounts for the large overall value, $\overline{FR}$ = 38.4 to achieve zero pressure gradient, longitudinally. Base pressures were not measured since they would closely approximate ambient static pressure. Calculations indicated that true drag would be one per cent less than measured drag. Since all compliant coated model tests were to be compared with rigid body tests, a further refinement was not considered necessary.

A similar appearing test body of different dimensions was prepared for the 1965 tests by the Davidson Laboratory of Stevens Institute. As shown on Figure 2-3, the slightly larger diameter is 6.78cm and the length of the one-piece forebody test section is 99.06cm. The short strain-gauge sting-mount portion of 7.62cm is shorter, but the towing attachment is affixed to the shorter afterbody section. More compact stabilizing fins are evident at the rear just ahead of the short boat-tail. The afterbody section is 105.66cm in length or 113.28cm if the strain-gauge section is combined with it. The total length of the test body is 212.34cm. The initial date of introduction of this second generation tow body is not as yet clear.

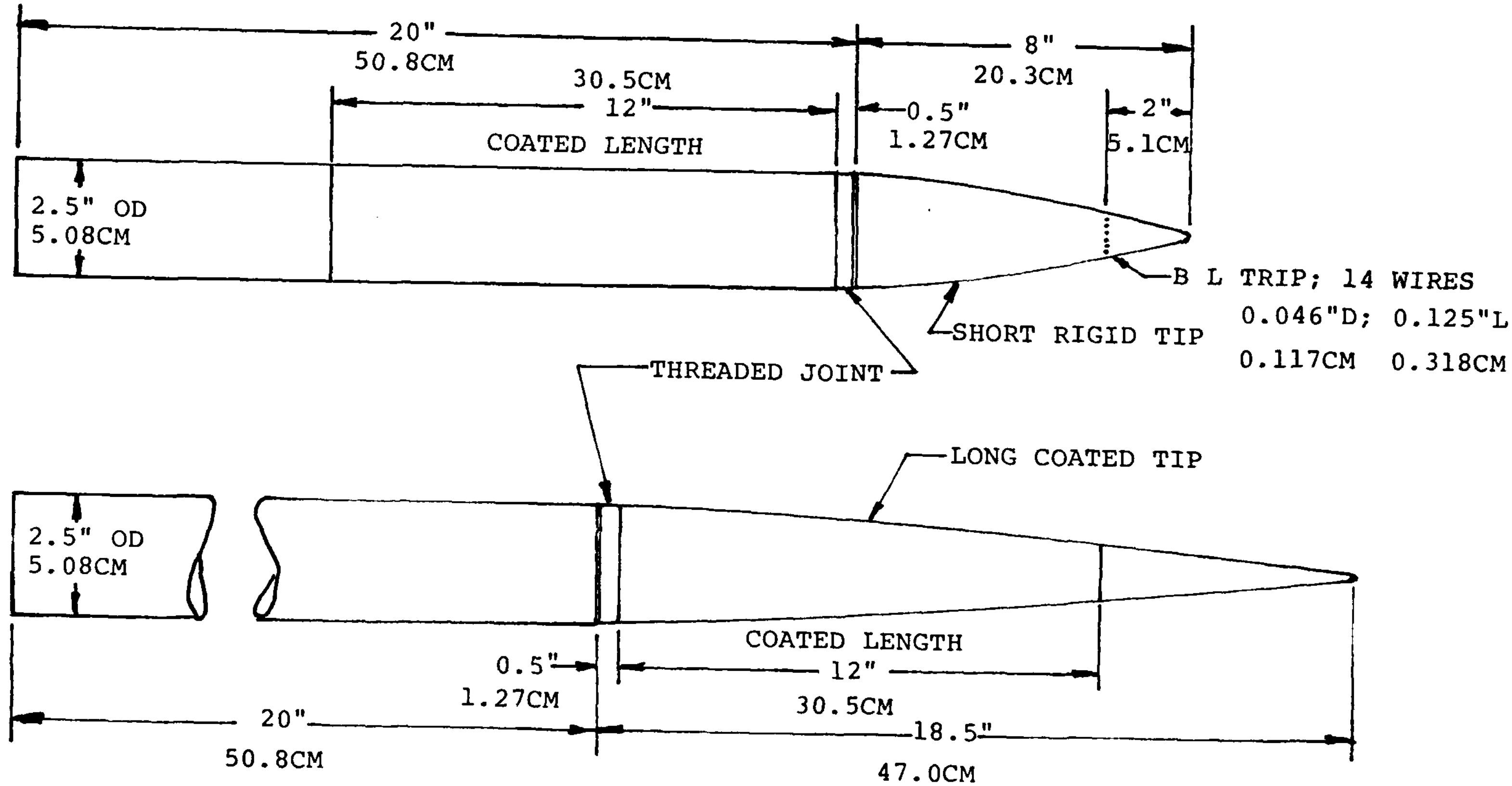


FIGURE 2-2 EXTERNAL DIMENSIONS OF 6.35CM DIAMETER TEST BODIES

TABLE 2-1

DISTANCE FROM TIP		DIAMETER OF TIP	
INCHES	CM	INCHES	CM
0.25	0.635	0.30	0.762
0.5	1.27	0.45	1.143
1.0	2.54	0.68	1.727
2.0	5.08	1.00	2.540
3.0	7.62	1.21	3.073
4.0	10.16	1.39	3.531
6.0	15.24	1.67	4.242
8.0	20.32	1.89	4.801
10.0	25.40	2.08	5.283
12.0	30.48	2.23	5.664
14.0	35.56	2.35	5.969
16.0	40.64	2.44	6.198
18.0	45.72	2.49	6.325

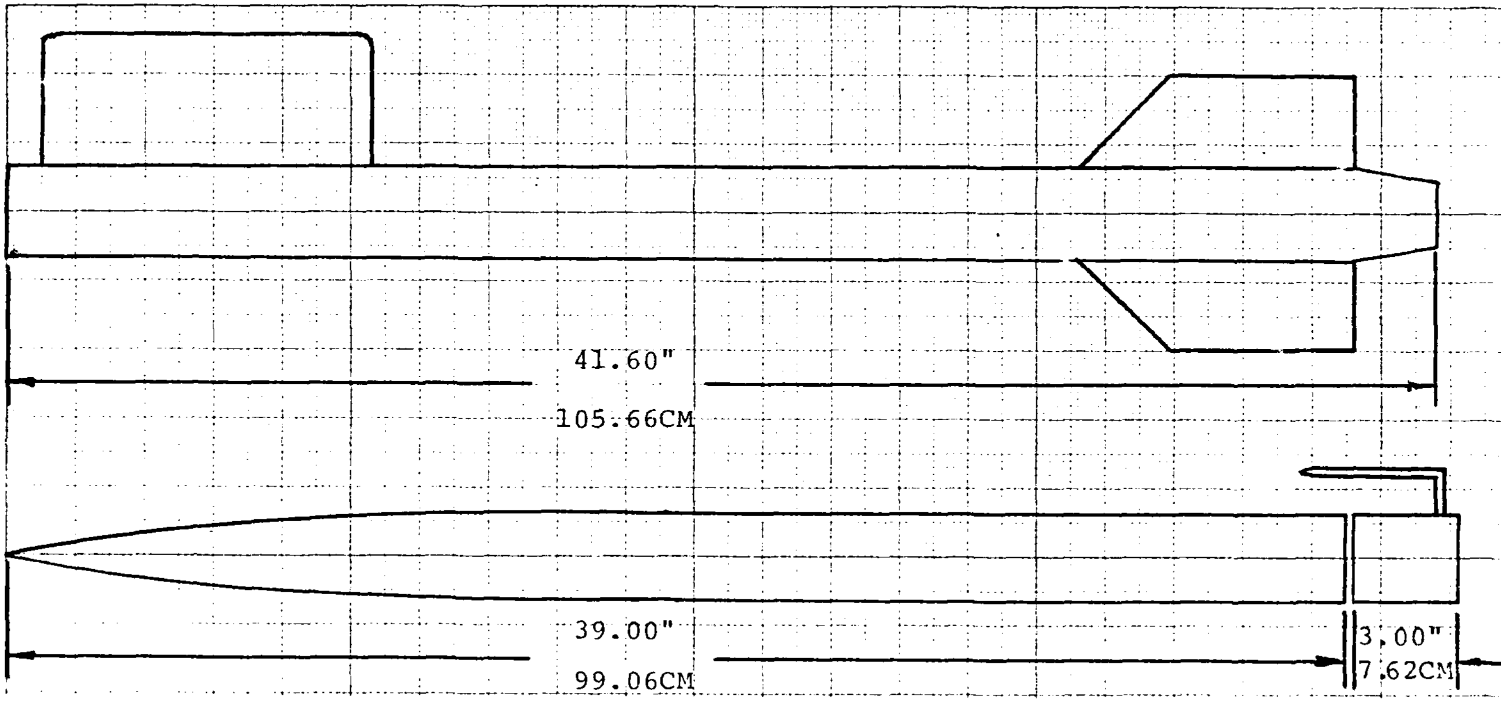


FIGURE 2-3 6.78CM TOWED BODY WITH RIGID AND COATED FOREBODIES

TOWING TECHNIQUES

The first three years of experiments with towed bodies utilized a 4.877m flat body speed boat with twin 85 bhp outboard engines. This towing boat is shown on Figure 2-4 and again on Figure 2-5. The bodies were towed by a cable winch off the starboard side by nylon coated stainless steel cable, 0.2337cm diameter. The lanyard length was varied between 3.05 and 30.5m with the recorded transition measurements, on a rigid body, independent of lanyard length. A lanyard length of 5.18m was selected for subsequent tests. This would indicate that the overpressure field from the propellers was recovered due to the long cylindrical shape of the test body ahead of the gap by the strain-gauge.

Side sway of the body under tow was eliminated by positioning the tow point 3.81cm aft of the center of gravity. Under these conditions, a "negligible" angle of attack would result in the speed range of the test. The maximum reported Reynolds number of = 15×10^6 corresponds to a speed of 13.82 m/sec (26.867 knots). This value approaches the nominal 30 knot speed capability of the boat used during 1956-1960.

To obtain a nominal 10 knot speed increase, a 4.877m catamaran speed boat with twin 80 bhp outboard engines was purchased and used in 1960 and later. This towing boat is shown on Figure 2-6. Using this craft, the problems associated with the lanyard tow were eliminated, but the overpressure of the boat hull loading was incurred. An hydraulically operated strut raised the single point towed-body to 15.2cm above mean waterline and to 106.7cm below. Towing depths of 52cm and 107cm with a compliant coating model showed negligibly small differences in drag results. Careful analysis of this interference pressure from the hull unit area loading is warranted.

For this new configuration of test body, hull, and propellers, single-engine side tow tests were run 122cm outboard of the starboard engine/propeller combinaton. This position was 274cm from the port engine/propeller combination operating singly.

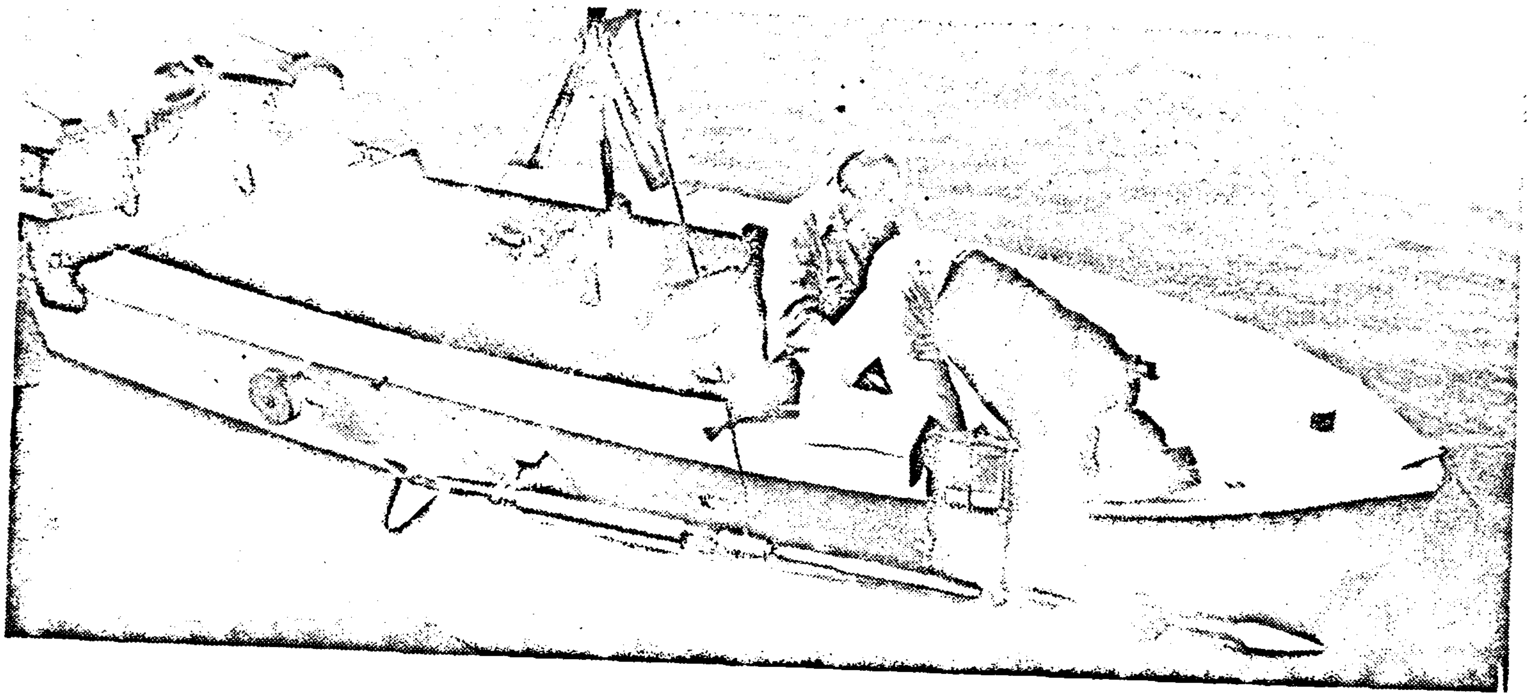


FIGURE 2-4 6.35CM DIAMETER TOWED BODY SECURED TO FLAT BOTTOM 30 KNOT TOW BOAT

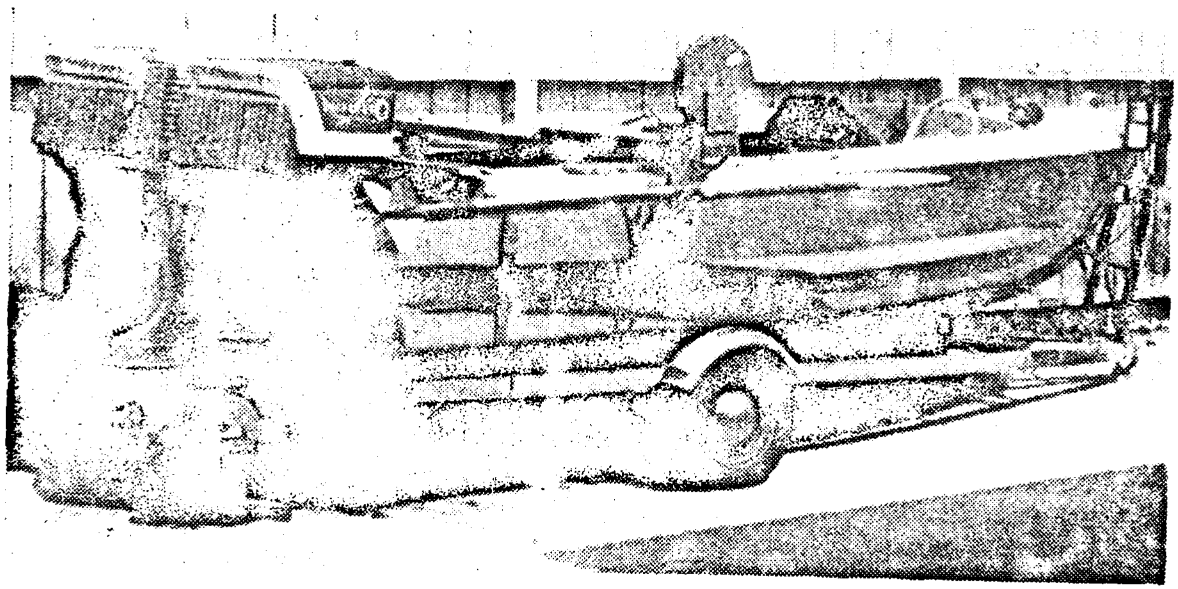


FIGURE 2-5 6.35CM DIAMETER TOWED BODY MOUNTED ON THE FLAT BOTTOM 30 KNOT TOW BOAT

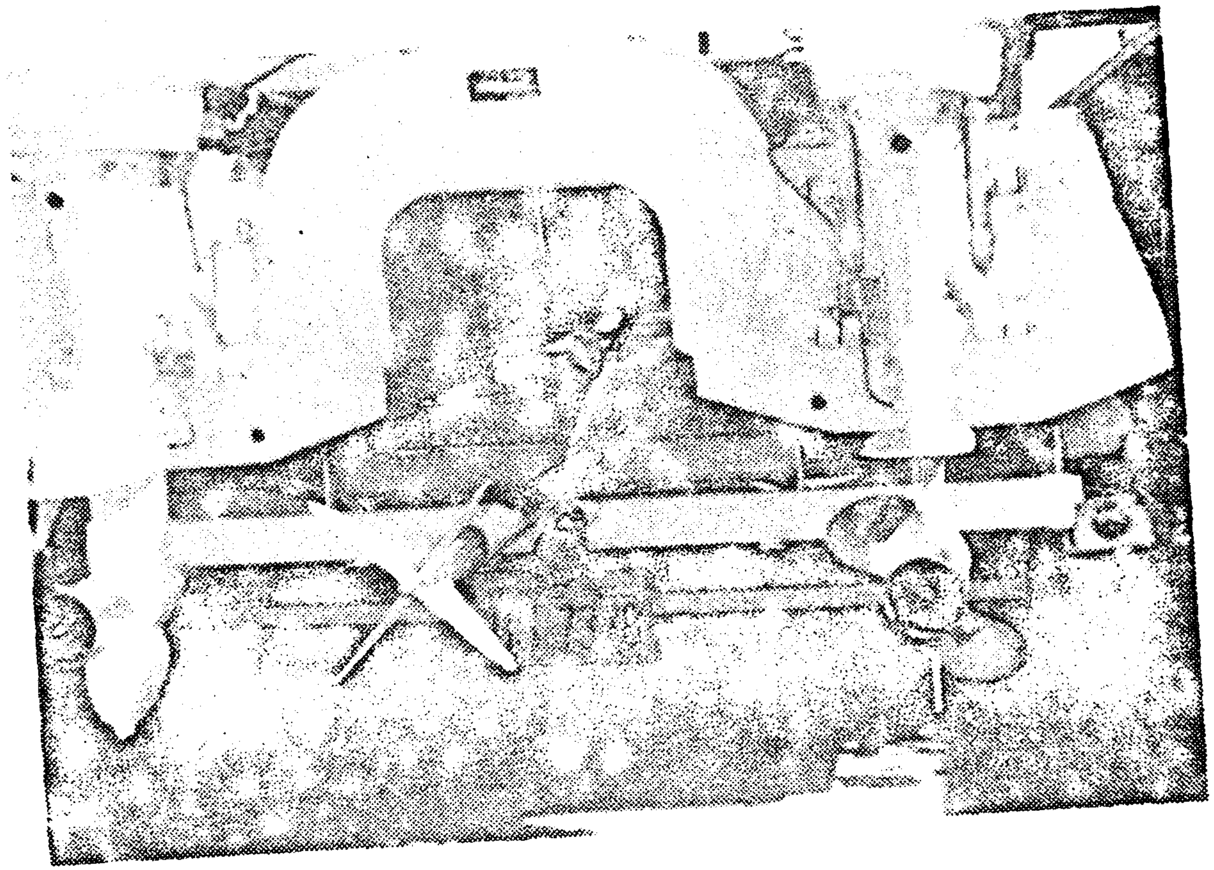


FIGURE 2-6 THE TOWED BODY AND THE TOWING STRUT INSIDE THE TUNNEL OF THE CATAMARAN 40 KNOT BOAT

The conclusion was that acoustic interference was negligibly small. Therefore the positioning of the strut-mounted model on the catamaran centerline to provide an average acoustic range of 244cm from the nearest propeller was adequate.

BUOYANT BODIES

Three designs for buoyant bodies to be used in submerged release tests were described furing the period 1967-1975. The first body was comprised of an ellipsoid forebody, cylindrical midbody and conical afterbody as illustrated by Figure 2-7. This body introduced an adverse pressure gradient for the final time. The source document includes detailed calculations but no measured weights. No experimental data sources specifically cited this $\overline{FR} = 12.0$ body which was to be machined to a wall thickness of 0.254cm and fitted with internal ring stiffeners. There was discussion at a later point in time about the region of turbulence generated by high drag, circular wire screen which was to slow the rate of descent. If that turbulence region were not moved aside by an underwater current, the order of magnitude higher ascent velocity of the buoyant body would reduce the turbulence parameter to an acceptable level.

The second buoyant body was a $\overline{FR} = 8$ Reichard (not identified further) body with a tangent conical (14° included angle) afterbody as shown by Figure 2-8. The maximum diameter was 15.24cm and the overall length was 121.92cm. With a three-layer 0.1524cm coating in three 120° sectors with an epoxy bonding agent, the maximum diameter was 15.54cm. The first body of this design was machined from tubular pieces to 0.254cm thickness from cotton weave phenolic material and cost $2000 ($ FY 67) in vendor charges. After eight tests with a compliant coating and a (heavily doped) "rigidized"coating, that body surfaced from an errant launch in December 1967 and drifted away before the launcher could be recovered and the outboard re-started. A second version of this design was produced in molded halves of Durathane Foam AZ3376 (0.09612 gm/cm^3) which had to be bonded together and sealed externally with three coats of fiberglass resin.

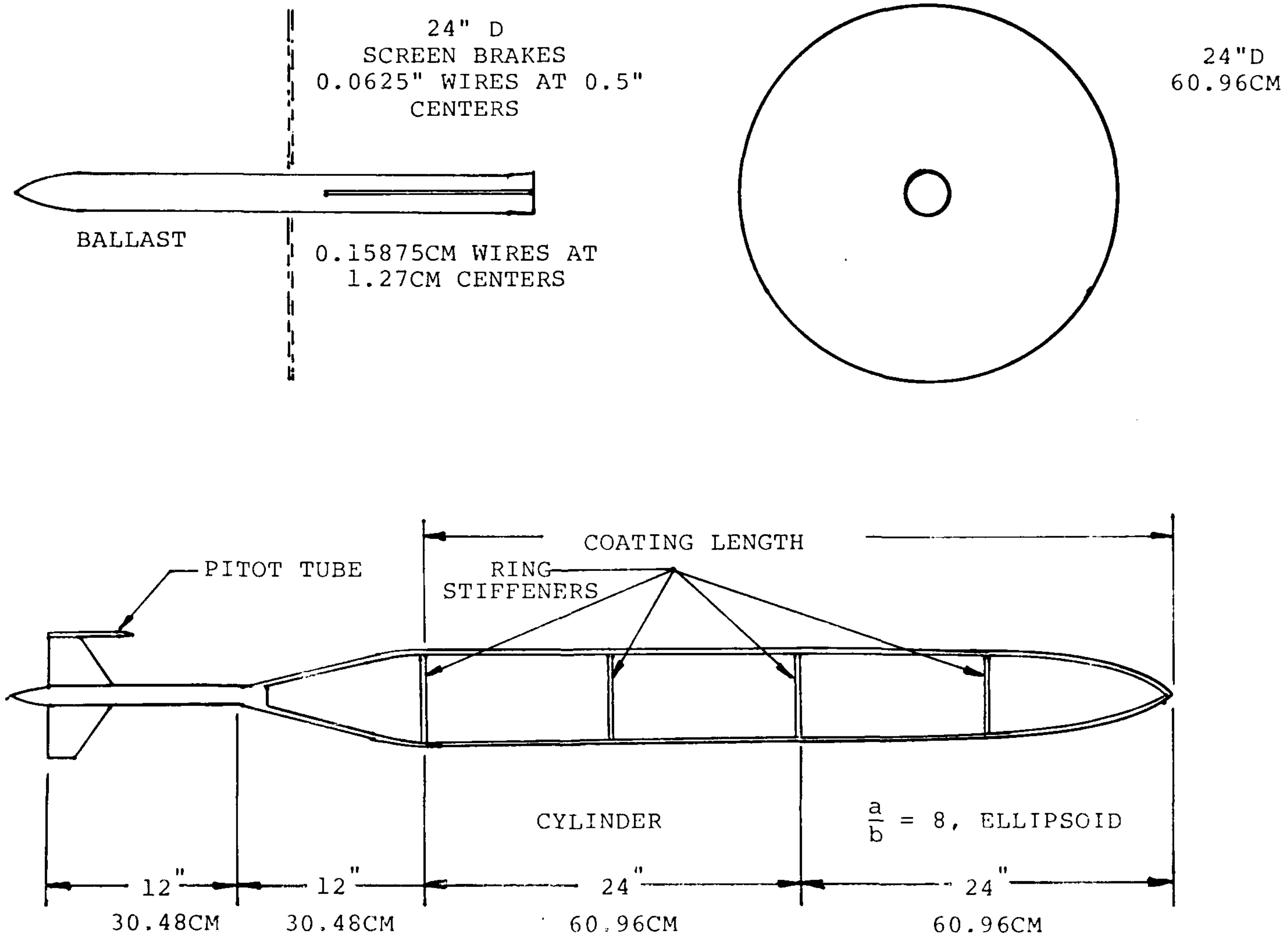


FIGURE 2-7 1967 POP-UP TEST BODY 1/10 SCALE ELLIPSOID-CYLINDER

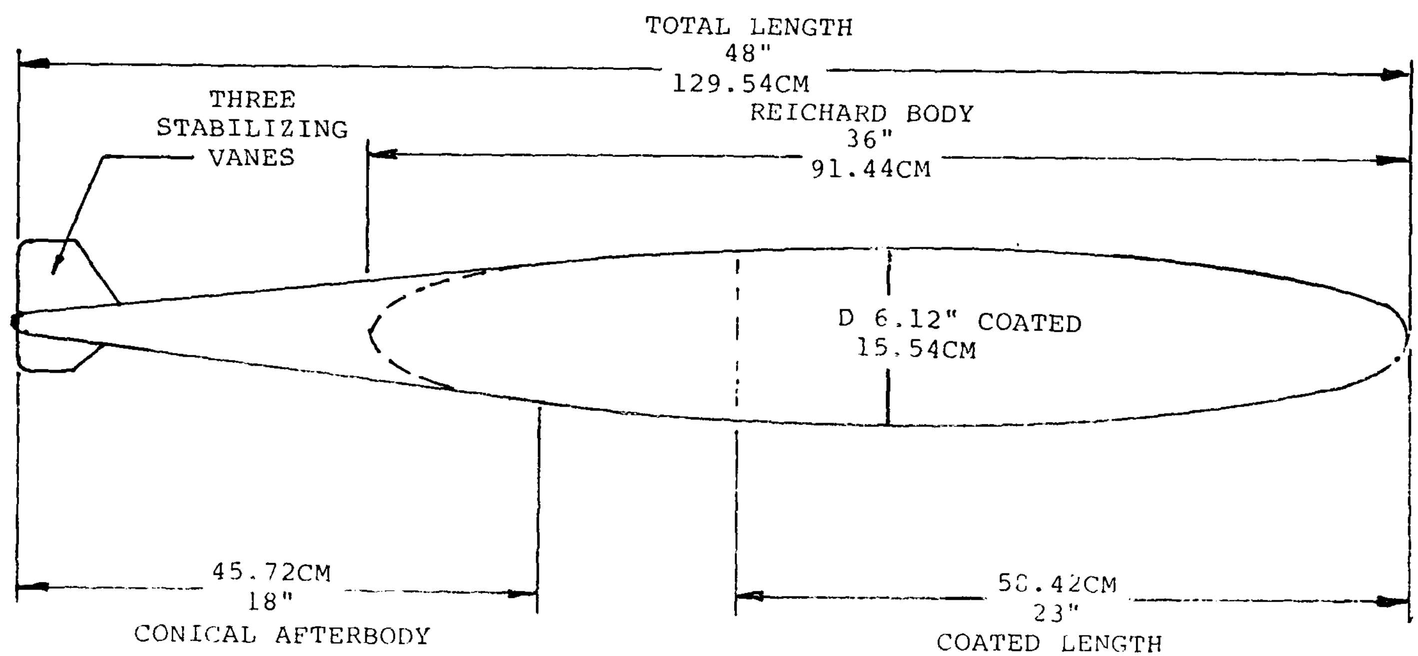


FIGURE 2-8 POP UP REICHARD BODY FOR COATING TESTS

A maximum pressure manometer was added in a 7.62cm cylindrical extension at the rear. This 129.54cm body is shown in cross-section on Figure 2-9 to illustrate the cylindrical cavities. A terminal dynamics pressure sensor, when installed added a further 10.16cm to the overall length. The comparable vendor cost was $200 per body ($ FY 67). Two bodies were prepared one each for separate rigid and compliant coating tests as permitted by the lower costs of fabrication. Eight tests were conducted in March 1968.

The third buoyant test body of $\overline{FR}$ = 6.15 was a body of revolution with transverse sectional areas corresponding to those of a 0.667 linear scale "whitesided" Dolphin of 182.88cm length. The two halves of the body were molded of urethane foam whose density was 0.1602 gm/cm^3. An inboard profile of the Dolphin body is shonw on Figure 2-10. It has a 19.81cm diameter and an overall length of 121.92cm. The wall thickness varies from 1.27cm at the ends to 5.08cm at 37.5 per cent of length to meet impact loads when falling back to the surface of the water. An overall view of the coated and uncoated exteriors is given by Figure 2-11. The inside and outside body ordinates are given by Table 2-2.

BUOYANT BODY RELEASE

The first buoyant body release system (1967) may have been only a design as was discussed for the ellipsoid-cylinder-cone buoyant body. It (would have) employed the large wire grid to slow descent to launching depth as shown on Figure 2-7.

The second buoyant body release system defintely was in use from 1968 to at least 1971. The release system is fully described on Figure 2-12. It should be noted that during the period of its use the launching depth was decreased from 32.00m to 22.86m when this was found to have no effect on the experimental result. Upon release of the positively buoyant body, the release mechanism would start to sink until restrained by the ring float on the surface. The motion of the tubular float was

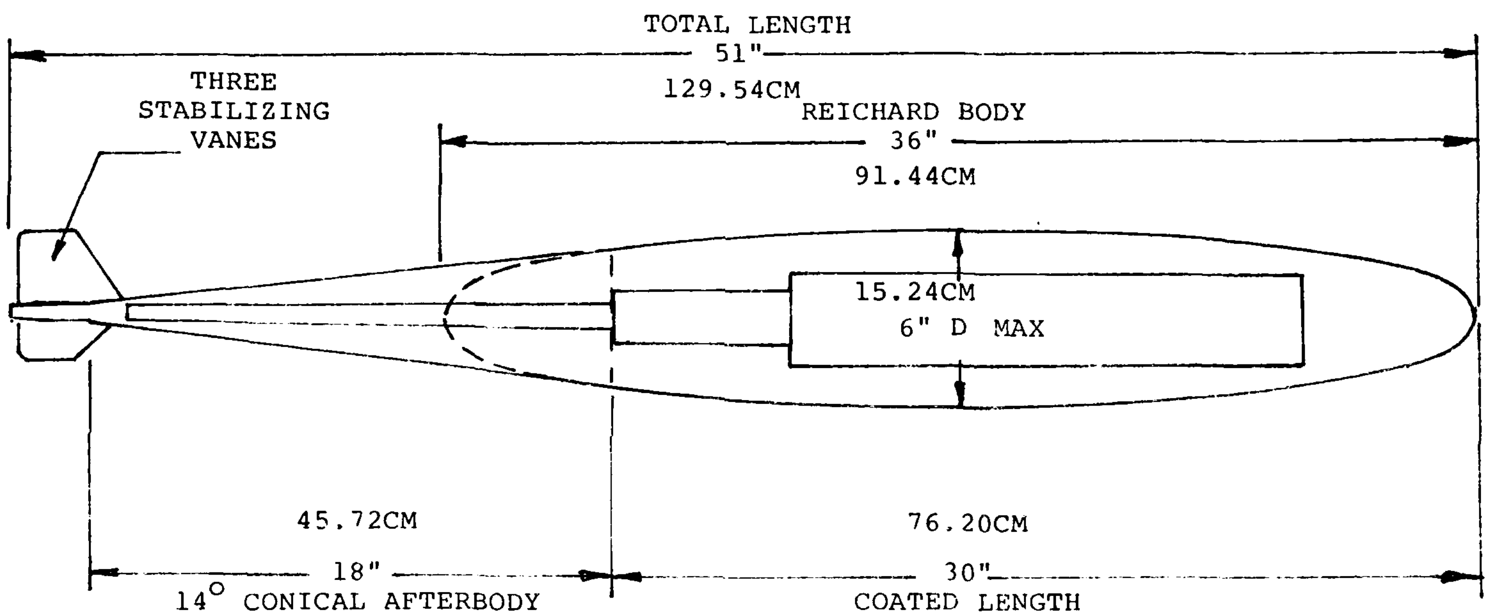


FIGURE 2-9 MOLDED POP-UP BODY FOR COATING TESTS RIGID BODY DIMENSIONS

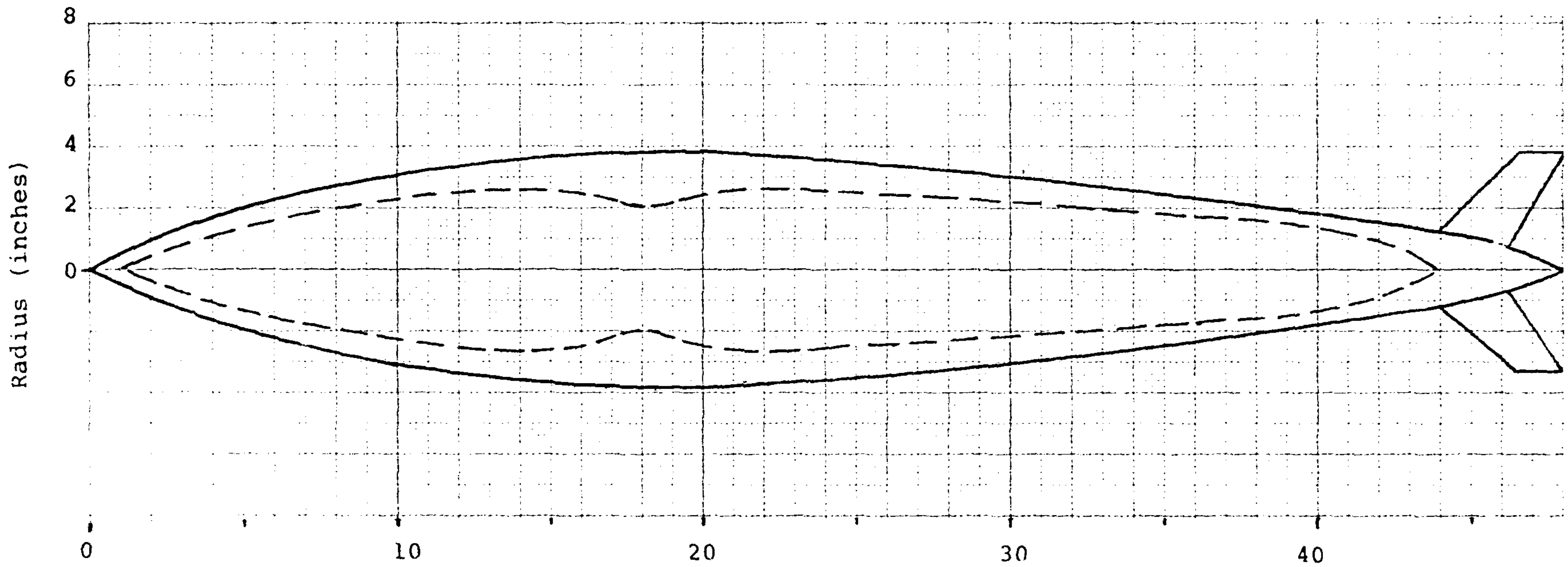


FIGURE 2-10 18.29CM DIAMETER POP-UP TEST BODY, COORDINATES IN TABLE 2-2

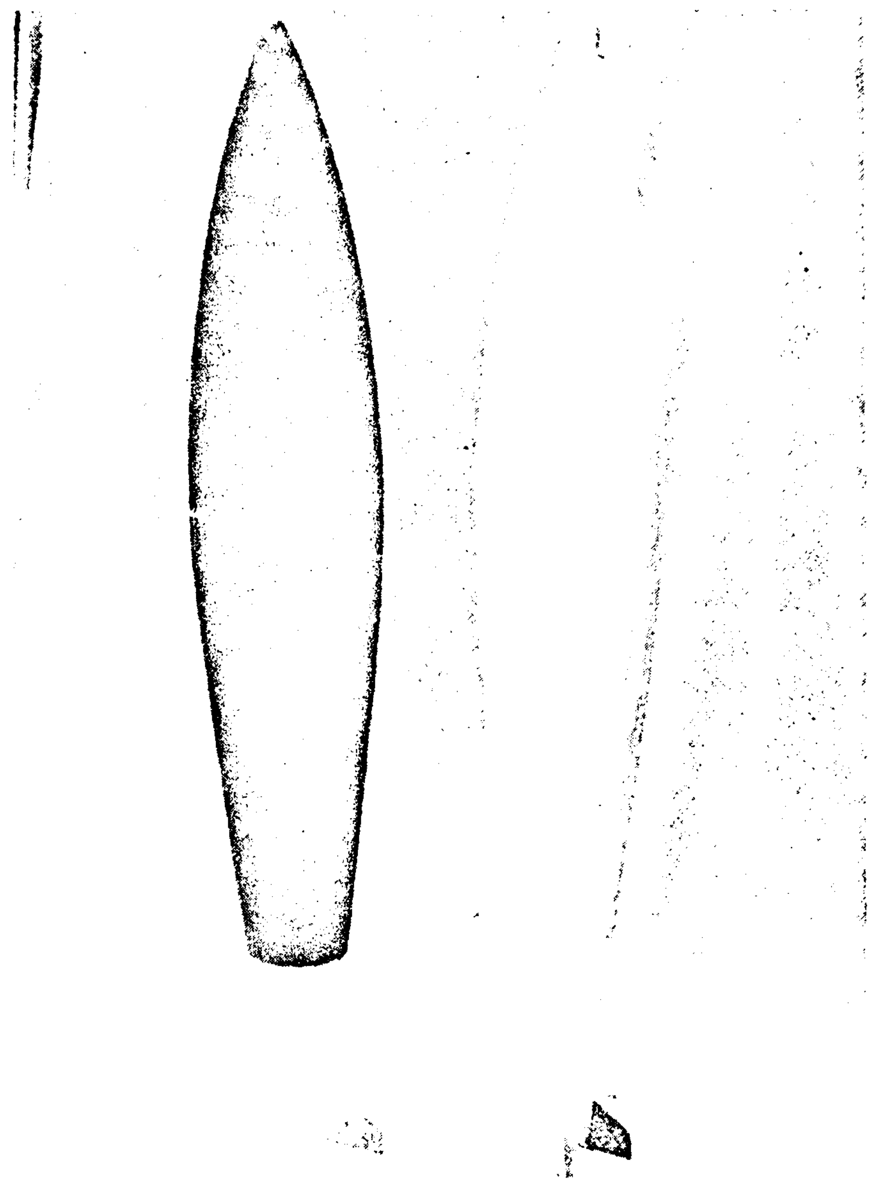


FIGURE 2-11 COATED AND UNCOATED TEST BODIES

TABLE 2-2

STATION FROM TIP INCHES	STATION FROM TIP CM	OUTER DIAMETER INCHES	OUTER DIAMETER CM	STATION FROM TIP INCHES	STATION FROM TIP CM	INNER DIAMETER INCHES	INNER DIAMETER CM
2.0	5.08	2.0	5.08	1.0	2.54	0.0	0.00
5.0	12.70	4.1	10.41	3.0	7.62	1.6	4.06
10.0	25.40	6.2	15.75	6.0	15.24	3.3	8.38
15.0	38.10	7.5	19.05	11.0	27.94	4.8	12.19
20.0	50.80	7.6	19.30	16.0	40.64	5.0	12.70
25.0	63.50	6.9	17.53	18.0	45.72	4.0	10.16
30.0	76.20	5.8	14.73	21.0	53.34	5.2	13.21
35.0	88.90	4.9	12.45	26.0	66.04	5.0	12.70
40.0	101.60	3.6	9.14	31.0	78.74	4.2	10.67
45.0	114.30	2.2	5.59	36.0	91.44	3.5	8.89
48.0	121.92	0.0	0.00	41.0	104.14	2.4	6.10
				44.0	111.76	0.0	0.00

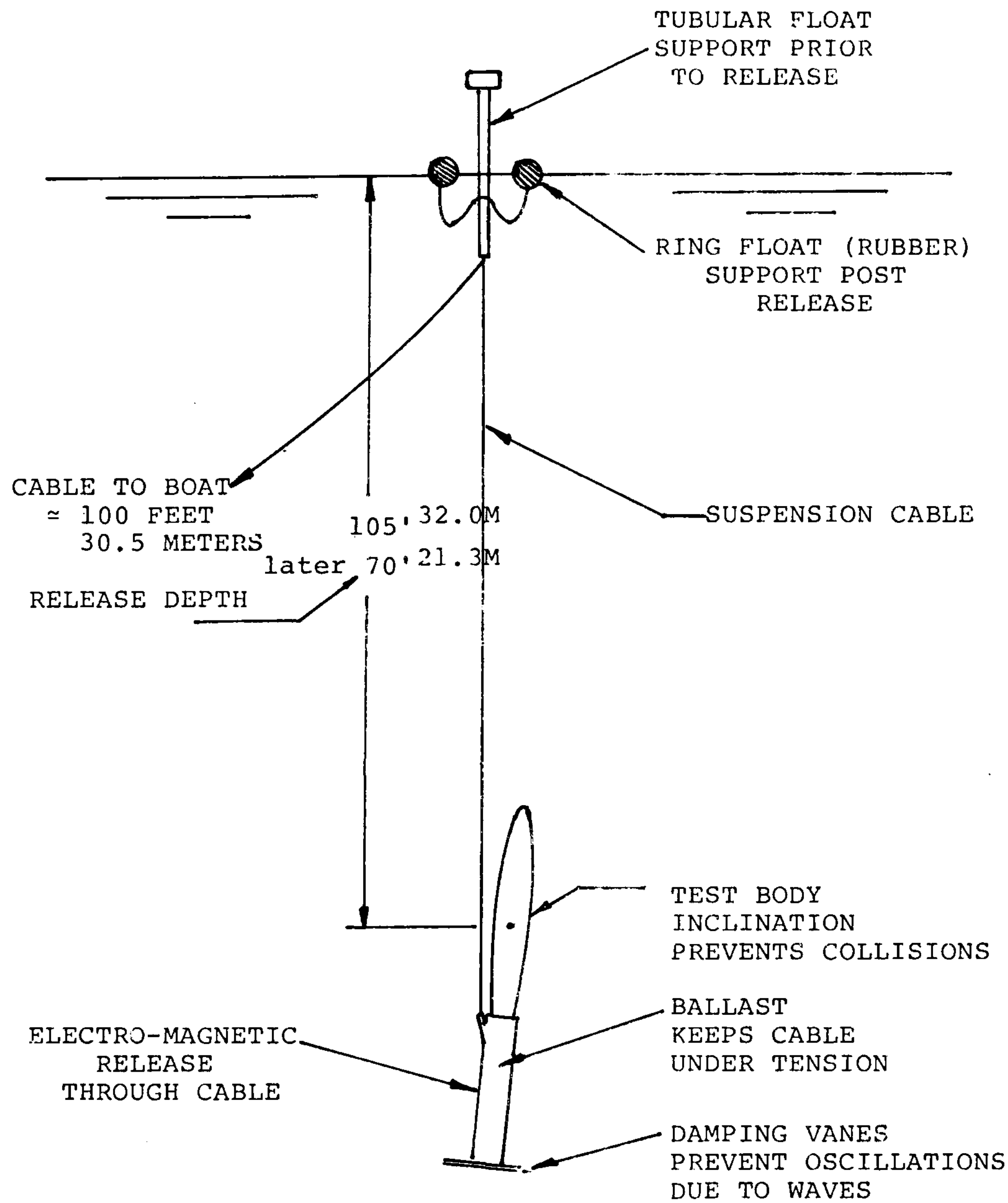


FIGURE 2-12 SCHEMATIC OF THE "RUN-DURATION" TEST TECHNIQUE

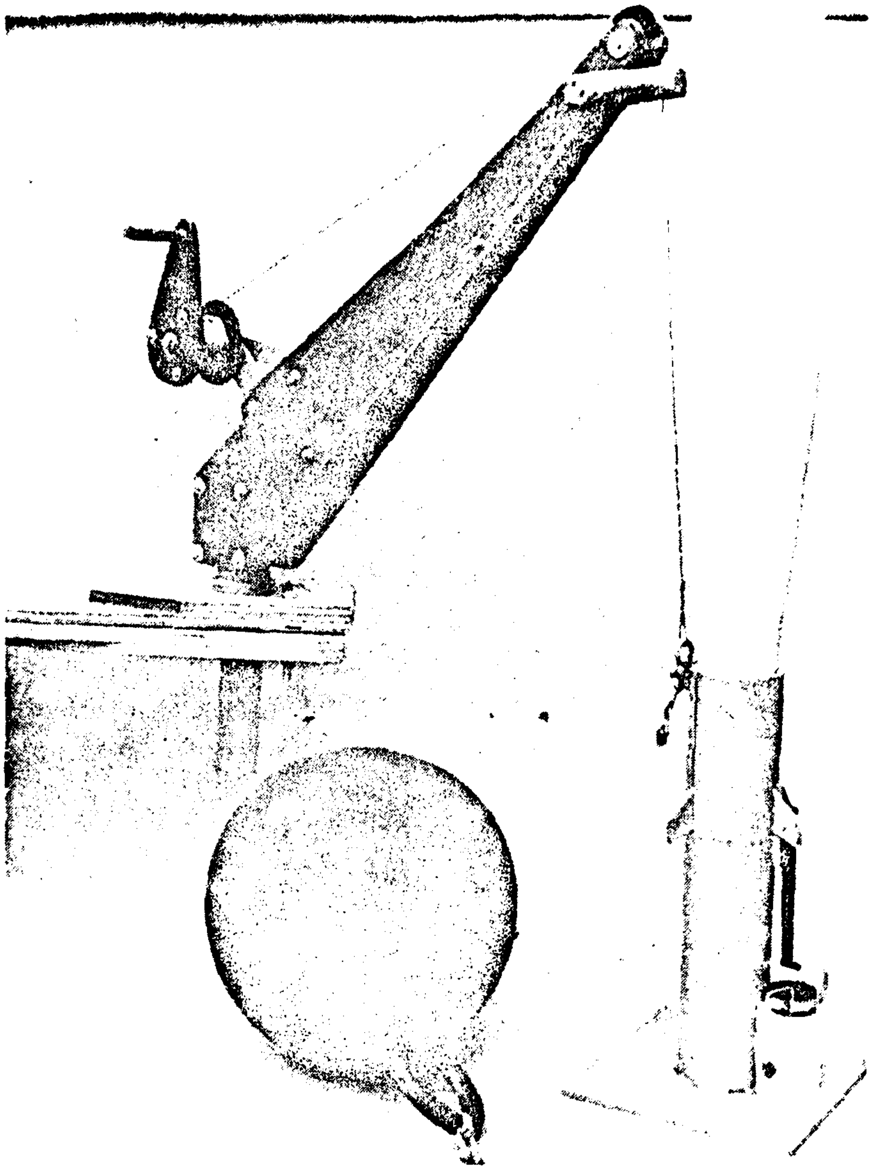


FIGURE 2-12 OCEAN TEST EQUIPMENT - LAUNCHER WITH BODY, HOIST, AND RUBBER FLOAT

recorded by a movie camera. The camera speed was checked by a stopwatch which was also recorded by the same movie camera. This was a substantial improvement over the hard operated stopwatch timing of the first of the buoyant body release tests. The base plate of the launcher serves as a stand for handling on the bottom of the boat and serves as a damping surface for vertical motions induced by surface waves. The uncertainty of release depth and trajectory length arising from surface wave height was not resolved. It was minimized by testing on days when wave height was 61cm or less.

The third buoyant body release system was in use circa 1972-1975. This release system is illustrated on Figure 2-12. The improvements were for the convenience of the experimentalists rather than to improve the accuracy of the experiment. A winch to raise and to lower the release system eliminated a major chore of hand hauling. A spherical buoy supported the net weight of the loaded release system before launch and the weight of the unloaded system after launch. The most significant change was to photographically record the duration of the leap of the body into the air and derive the resistance coefficient from the relation:

$$C_r = \frac{B-W}{A_w \frac{\rho}{2} V_t^2} = \frac{4(B-W)}{A_w g^2 \Delta t^2}$$

5 COMPLIANT DESIGNS

3. COMPLIANT COATING DESIGNS

GENERAL CONSIDERATIONS

In Kramer's first writing in 1961 as a RAND consultant he included photographs of testing equipment he had devised to measure basic properties of compliant coatings. However, specific values of these properties are for sub-optimized coatings cited in the February 1960 article in the Journal of ASNE. The pre-publication lead time suggests that such measurements were done as early as 1958.

The rubber industry uses the Shore A Durometer for measuring hardness of soft rubbers and the Shore D Durometer for harder products per ASTM Designation D2240. Kramer's skin stiffness tester appears similar in form, but he measured Young's modulus or modulus of elasticity E, unit load/unit strain (psi/in) instead of hardness on a scale of 0 to 100. This equipment is shown on Figure 3-1, with the calibrated weights. These stiffness values range from 22.15 to 69.22 kg/cm^3.

Damping characteristics of generally available rubber compounds increased as the modulus, M, was decreased. The overdamping of a coating for Modulus*= 50 psi lessened the drag reduction from that for M = 100 psi as much as occurred for M = 200 psi. Figure 3-2 shows the compliant coating damping tester which used a 14.17 gram piston of 1.27cm diameter dropped from a height of 5.08cm. At M = 3.515, 7.030, and 14.06 kg/cm^2 the measured potential energy losses per bounce (half cycle) were 51, 42, and 37 per cent, respectively. By calculating and subtracting out the impact loss, the remaining energy loss per half cycle, termed "Inherent Damping", was 41, 32, and 27 per cent for M = 50, 100, and 200 psi respectively. In metric units, M = 3.52, 7.03, and 14.06 kg/cm^2. Figure 3-3 presents the inherent damping, normalized to the value at M = 14.06 kg/cm^2, versus M as the independent variable. Note that Kramer incorrectly refers to this modulus, M, as modulus of elasticity, E. Note that the experimental relative damping factor increases as M decreases. Kramer's simplified theory showed

* per ASTM D412, Modulus = unit load to stretch a test piece to a given elongation. Kramer specified doubling the original length, i.e., 100 per cent increase.

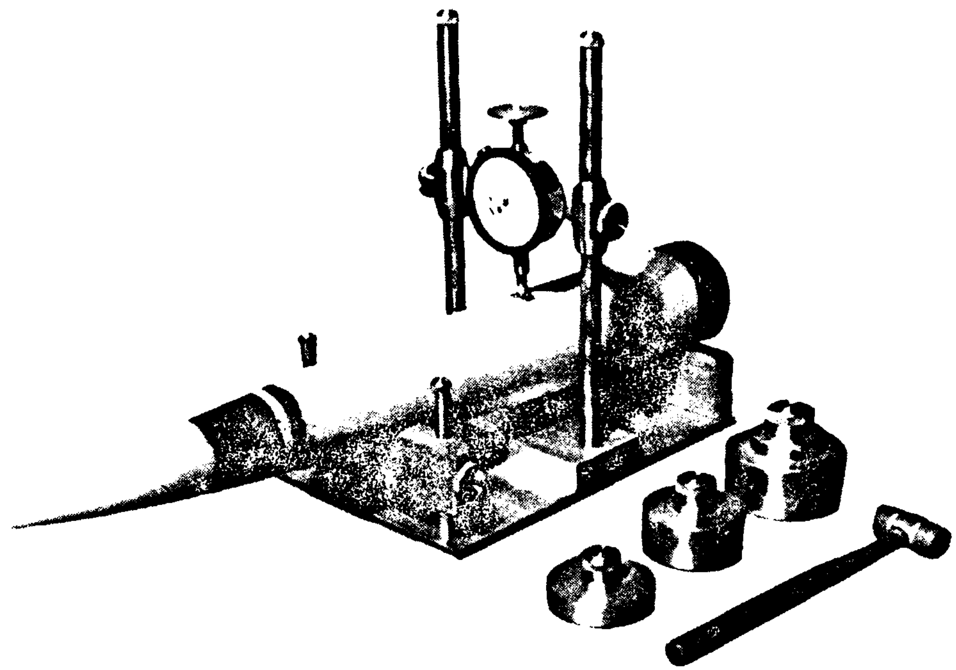


FIGURE 3-1 COMPLIANT COATING STIFFNESS TESTER

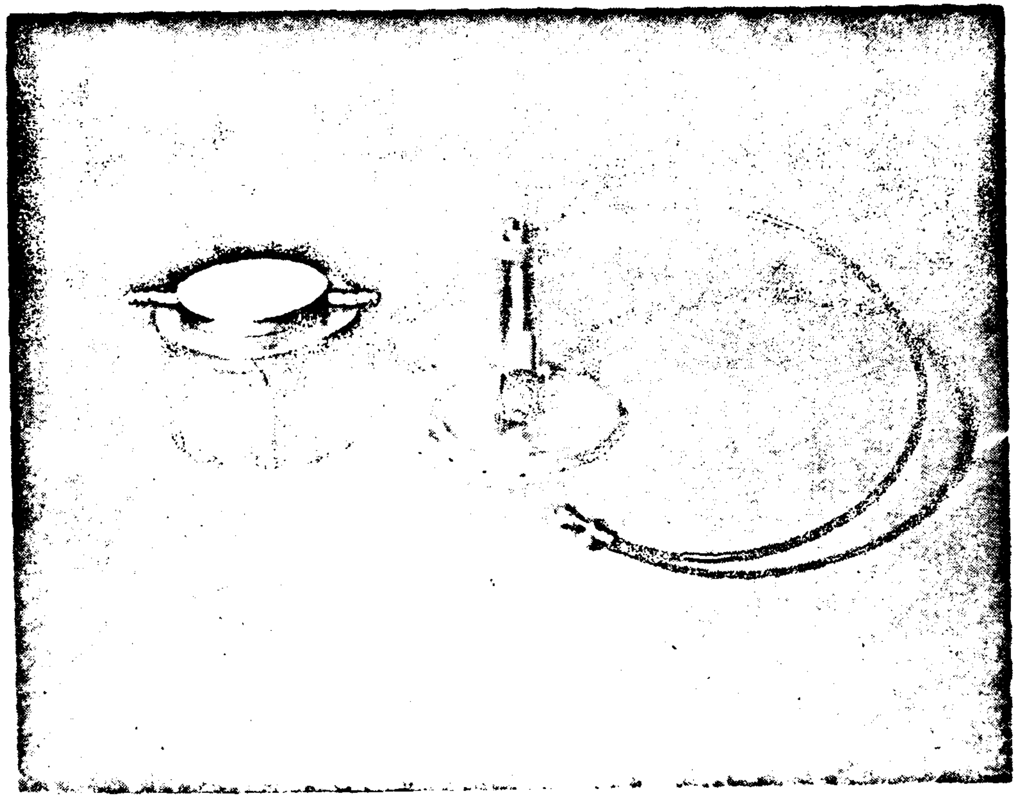


FIGURE 3-2 COMPLIANT COATING MATERIAL DAMPING TESTER

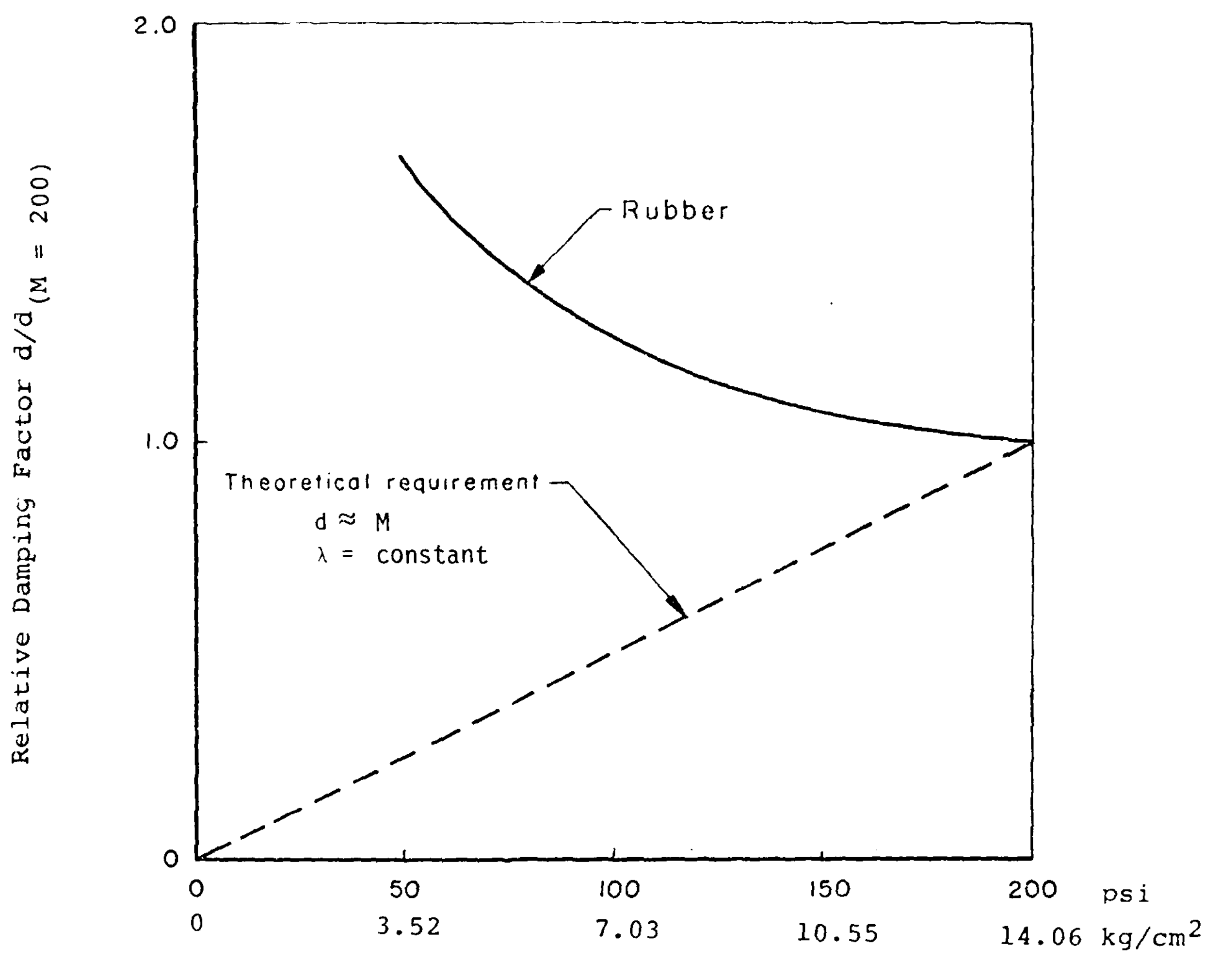


FIGURE 3-3 RELATIVE DAMPING VERSUS TENSILE MODULUS

that the opposite effect was required. It proved to be a slow process for Kramer to lead the rubber chemists in this direction, which was counter to their past experience. It was effected by the use of elasticizers, usch as dibutyl phthalate used in the polyisoprene compounded rubber of Table 3-1.

STUBBED COMPLIANT COATING

This coating, which evolved into the bottom layer of the successful three layer compliant coating, was so termed because of the short cylinders of length equal to diameter protruding from a diaphragm of thickness equal to 1.5 diameters. The stub spacing was 1.0 diameter laterally and about 0.75 diameters longitudinally in staggered columns, as shown on the lower portion of Figure 3-4. The earliest versions of the stubbed coating were molded of pure (gum?) rubber and were bonded directly to the test body. Water may have been used as the damping liquid before silicone fluids of widely differing viscosities were introduced. A thin substrate of dipped rubber seamless hose was introduced later so that the polyisoprene coating could be fluid filled before applying to the body. The substrate is shown at the top of Figure 3-4. A similar outer diaphragm of dipped seamless rubber hose was added to smooth and to perhaps seal the single axial and the several peripheral butt joints for the 30.5cm long and 61cm long coatings. The molded sheets were 20.3cm by 20.3cm. This outer diaphragm later was suboptimized separately and became the middle layer of the three layer compliant coating. A general impression of the stubbed coating is given by the sketch on Figure 3-5. Cross-sections of the initial and improved stubbed coatings are shown on Figure 3-6.

The damping by high viscosity fluid was intended for the longer wave length, lower frequency disturbances in the laminar boundary layer. The outer diaphragms were originally intended to damp the shorter wave length, higher frequency local turbulent disturbances. No mention was made of the very thin, highly resilient dope coating in the 1960 article.

TABLE 3-1

INGREDIENT	WEIGHT BY PER CENT
POLYISOPRENE	58.00
ZINC OXIDE	3.00
STEARIC ACID	0.60
METHYL ZIMATE	0.15
SULPHUR	1.15
AGERITE WHITE	0.60
CARBON BLACK	1.15
DIBUTYL PHTHALATE	34.75
ALTAX	0.60
	100.00

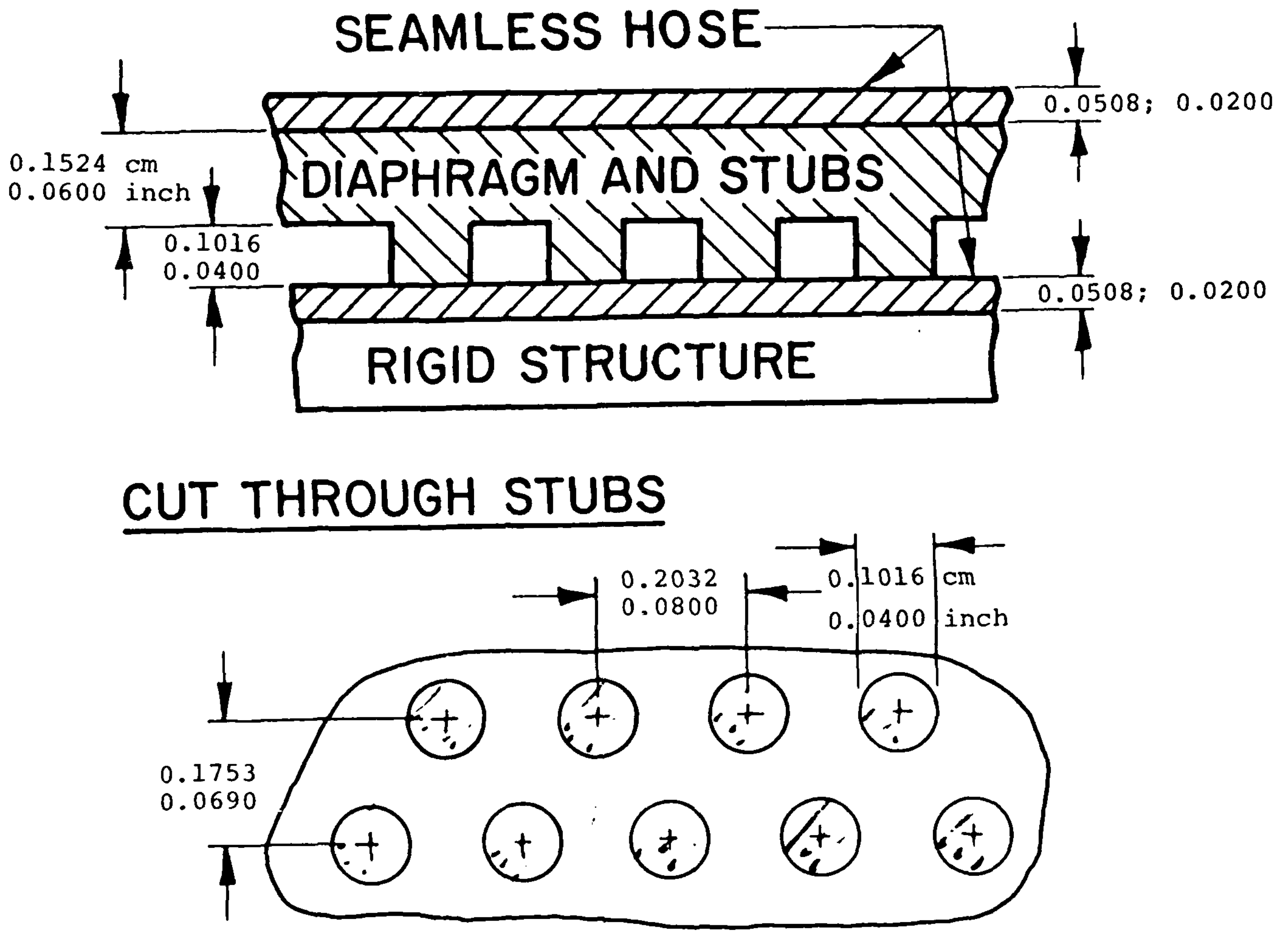


FIGURE 3-4 DIMENSIONS OF A STUBBED COMPLIANT COATING

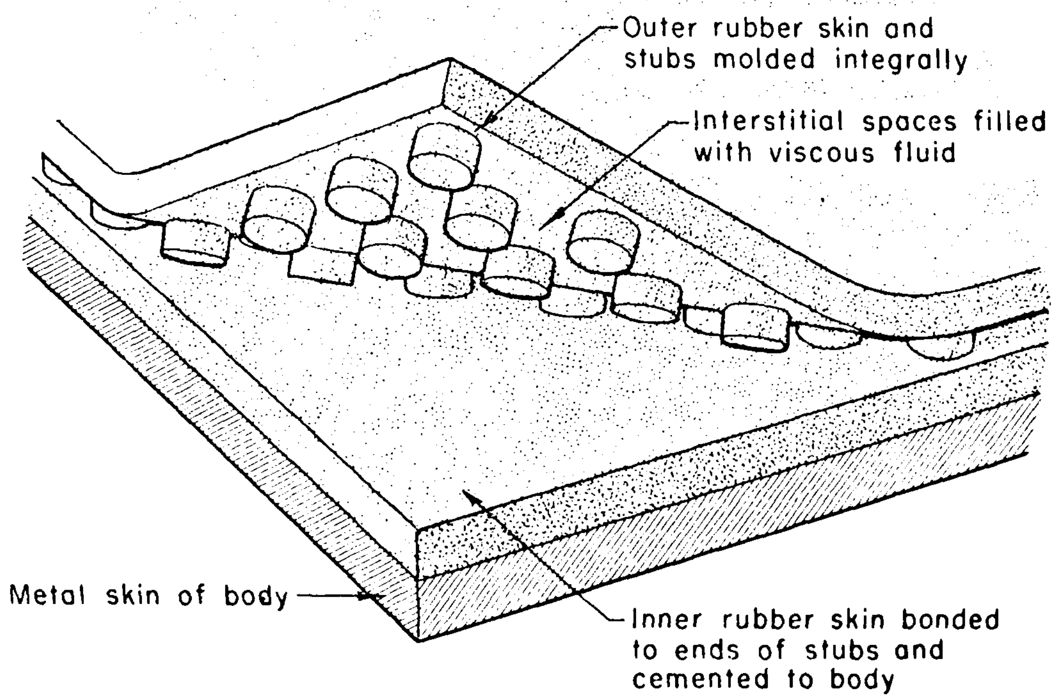


FIGURE 3-5 SCHEMATIC DRAWING OF STUBBED COMPLIANT COATING

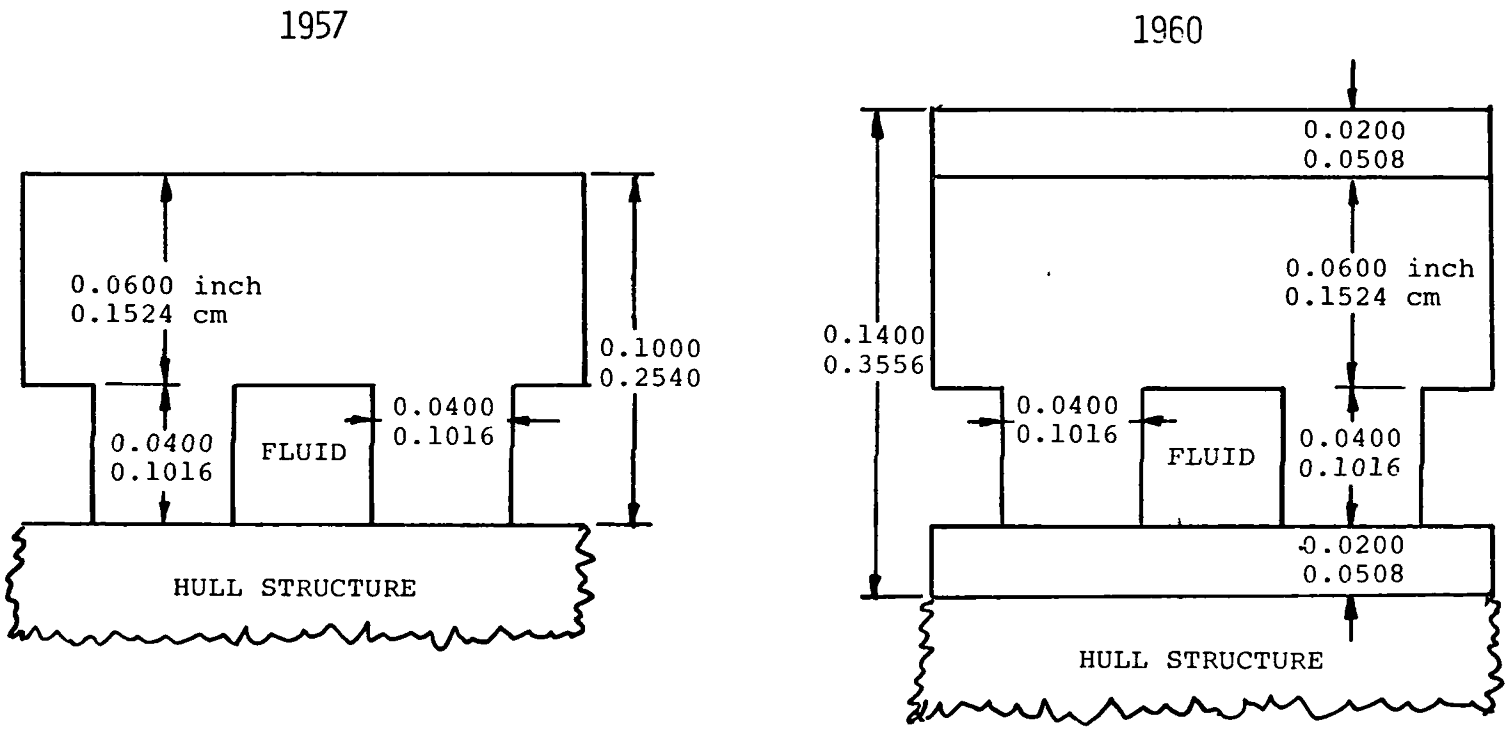


FIGURE 3-6 INITIAL AND IMPROVED STUBBED COATINGS

RIBBED COATING

Retesting of stubbed coating models after storage for about one year showed serious deterioration of the previously measured drag reduction. Kramer argued that strains were built into the coating as the 20.3cm sheets were formed around the model. Over a period of a year, stress relief occurred and a waveness of the surface was visible. The ribbed coating was developed to avoid this problem. Its anisotropy is longitudinal as applied. The transverse anisotropy suggest by Professor Marten Landahl in 1962 apparently was never tested. Although the ribbed coating, as shown schematically on Figure 3-7 was devised in 1960, it was first produced apparently in 1961 after the joint venture between Coleman-Kramer Inc. and the US Rubber Company was dissolved in December 1960. The ribbed mold was machined to provide only 5.08cm by 20.30cm sheets because of the machining costs. This resulted in four sheets with four longitudinal butt seams to coat the periphery of the 6.35cm diameter body. The May 1962 article in the Journal of ASNE provided the only reference to "feet" on the otherwise narrow bottoms of the individual ribs. This feature doubled the bonding area to the thin substrate as shown on Figure 3-8.

As mentioned in the stub coating discussion, the high viscosity fluid in the bottom layer was intended to damp the longer wave length lower frequency Tollmien-Schlicting disturbances in the laminar boundary layer. The outer diaphragm was intended to damp the shorter wave length higher frequency local turbulent disturbances. As shown on Figure 3-9, efforts were made to suboptimize the thickness of the outer diaphragm, which is later referred to as the middle layer. Also various rubber compounds were prepared in sheet form by the Elastomers Branch of the Non-Metallic Materials Laboratory of the Aeronautical Systems Division, WPAFB, Ohio. Four of these formulations are given by Table 3-2 and identified as Compounds D-2 for a Cis-4 polybutadiene, D-7 for a neoprene WRT, and D-21 and D-26 for two polyisoprenes, using Circosol 2XH and Dibutyl Phthalate for elasticizers, respectively. Later, a D-31 compound was prepared in sheet form, but its composition has not been found. Notice that Table 3-2 uses the term 100 per cent

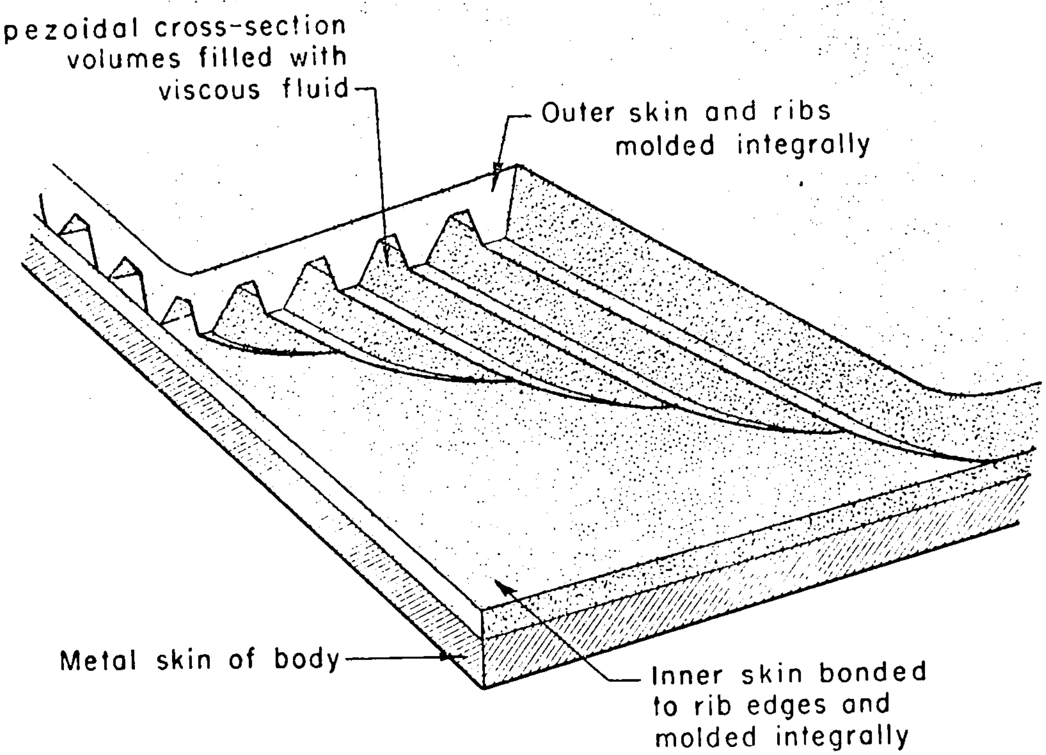


FIGURE 3-7 SCHEMATIC DRAWING OF RIBBED COMPLIANT COATING

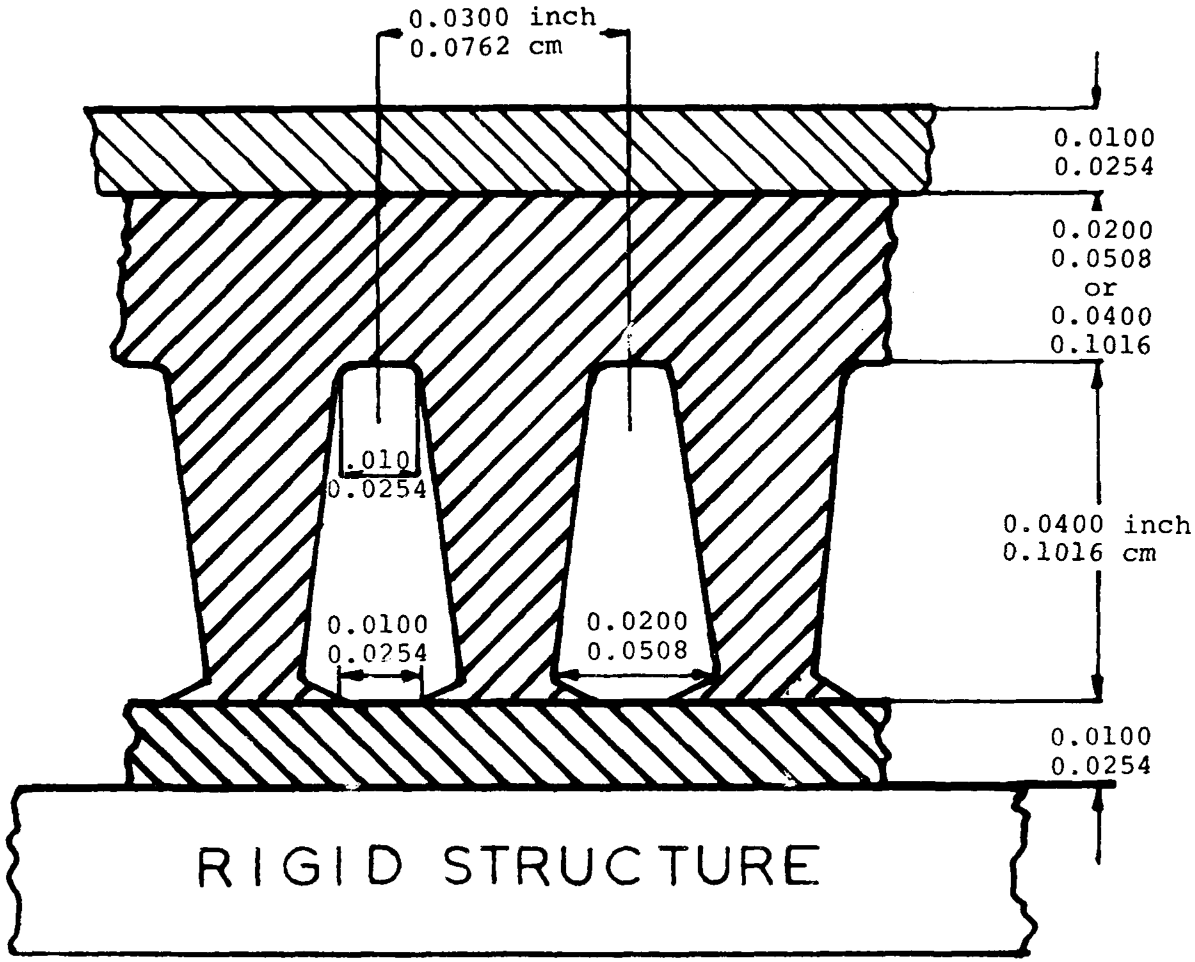
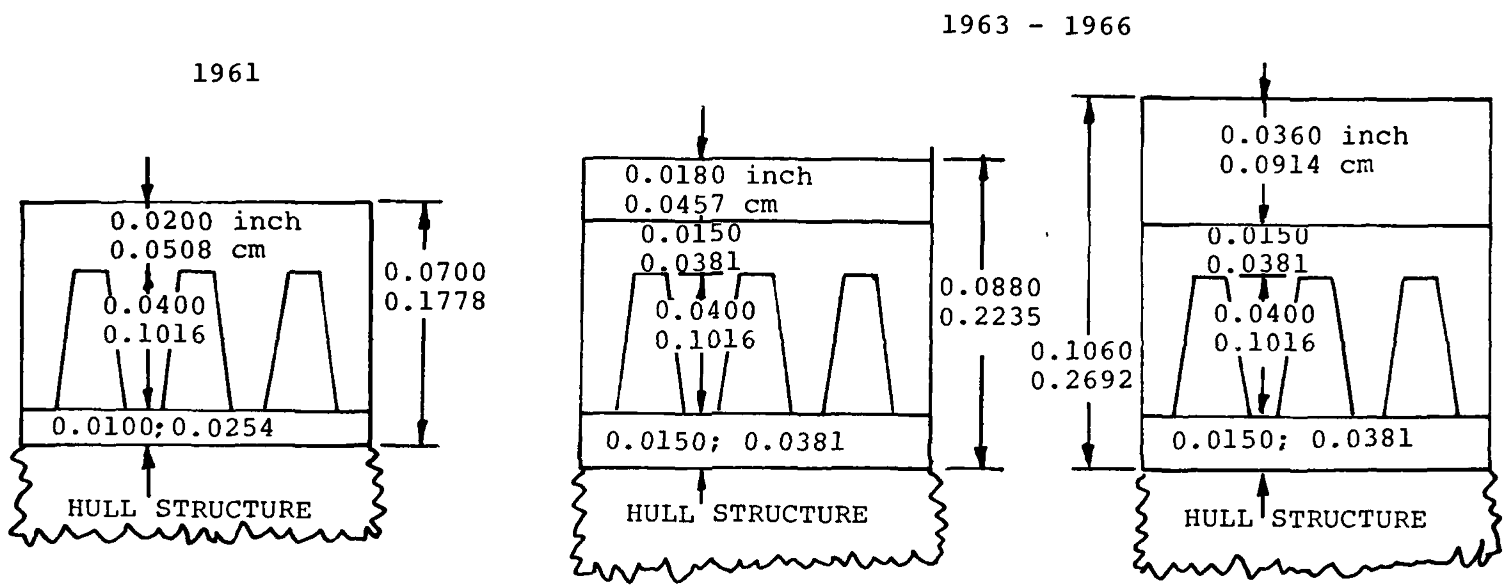


FIGURE 3-8 TRANSVERSE SECTION OF A RIBBED COMPLIANT COATING



INITIAL AND IMPROVED RIBBED COATINGS

FIGURE 3-9 INITIAL AND IMPROVED RIBBED COMPLIANT COATING

TABLE 3-2

OUTER DIAPHRAGM ELASTOMER COMPOUND

	FORMULAS			
COMPOUND NUMBER	D-2	D-7	D-21	D-26
CIS-4 POLYBUTADIENE	100	-	-	-
NEOPRENE WRT	-	100	-	-
POLYISOPRENE (CORAL)	-	-	100	100
CIRCOSOL 2XH	20	-	15	-
DICAPRYL PHTHALATE	-	40	-	-
ZINC OXIDE	5	5	5	5
MAGNESIUM OXIDE	-	4	-	-
STEARIC ACID	1	-	1	1
ANTIOXIDANT 2246	1	1	1	-
AGERITE WHITE	-	-	-	1
HAF CARBON BLACK	-	-	-	2
DIBUTYL PHTHALATE	-	-	-	60

TABLE 3-2 (CONTINUED)

OUTER DIAPHRAGM ELASTOMER COMPOUND FORMULAS

COMPOUND NUMBER	D-2	D-7	D-21	D-26
MBTS (ALTAX)	1	-	-	1
SULFUR	1.5	-	3	2
NA-22	-	0.5	-	-
MBT (CAPTAX)	-	-	1	-
TETRAMETHYLTHIURAM-DISULFIDE	-	-	-	0.4
CURE TIME, MINUTES	30	30	30	60
CURE TEMPERATURE, ^{o}F	310	310	290	290
PHYSICAL PROPERTIES AT ROOM TEMPERATURE				
100% TENSILE MODULUS, PSI	70	50	30	-
TENSILE STRENGTH, PSI	110	620	150	-
ELONGATION, %	500	740	1200	-
HARDNESS, SHORE A, POINTS	26	24	21	17

Tensile Modulus to describe this author's modulus, M, which was substituted for Kramer's improper use of "modulus of elasticity, E". The latter is widely used and accepted in the U.S. as the slope of the stress-strain curve.

The outer or third layer of the compliant coating was first mentioned in the May 1962 Journal of ASNE. Three spray coats of aircraft dope were added to the outer surface "to eliminate any uncertainty concerning surface smoothness". Polishing compound was used to polish the doped surface.

HOMOGENEOUS COMPLIANT COATINGS

An investigation was begun in 1965 to find an homogeneous material whose properties would match the suboptimized silicone fluid ribbed coating of the bottom layer. No response was found to the January 1965 inquire to DuPont, but Stillman Rubber Company of Culver City, California supplied test buttons of their SR-549-10 compound. An 0.045" (0.1143cm) thick "shirt" was ordered in August 1965. Its Shore A hardness value was 14. Kramer stated its properties matched the tensile modulus, M, and damping characteristics of the ribbed coating filled with 14,000 centistokes silicone fluid.

The important advantage was to eliminate the problems of sealing the high viscosity silicone fluid in the bottom layer. The overall layer is tougher and more durable. The preparation and installation of the three-layer compliant coatings are greatly simplified.

The first complete three-layer coating reported was composed of an 0.040" (0.1016cm) high damping bottom layer, a high resiliance 0.020" (0.0508cm) middle layer and a two-coat sprayed butyrate dope outer layer 0.0002" (0.0005cm) thick, of very, very high resiliance. This compliant coating was first described in the 1969 Yearbook of the German Society of Aviation and Space. The schematic drawing is given on Figure 3-10. The rubber compounds for the bottom layer and the middle layer are given by Table 3-3.

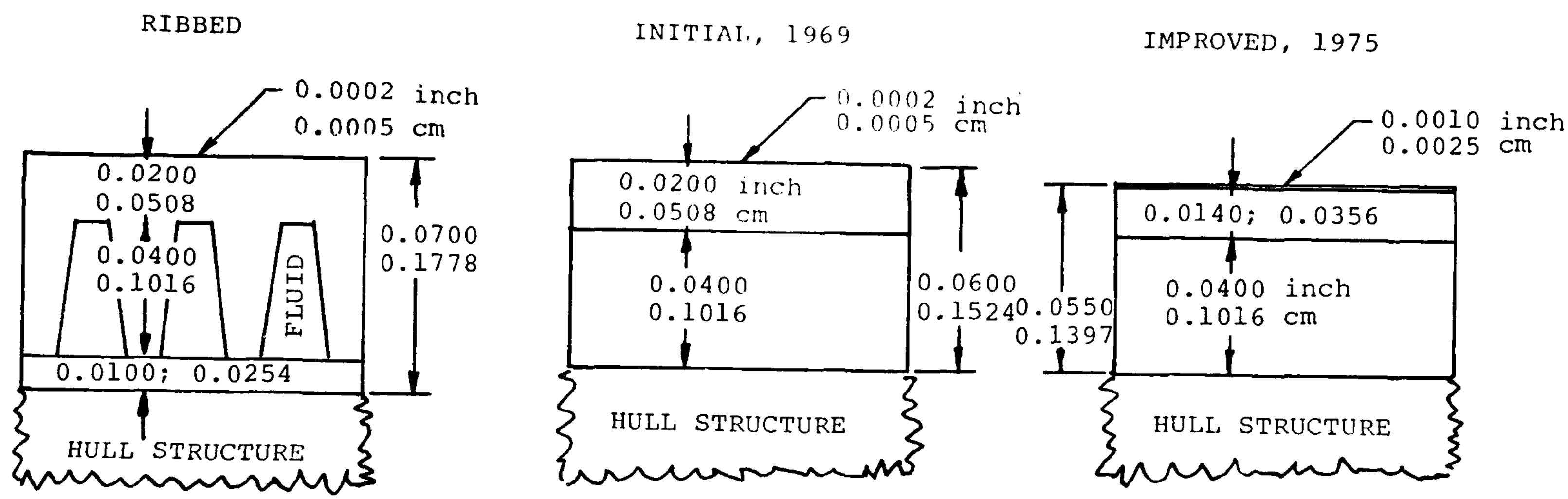


FIGURE 3-10 INITIAL AND IMPROVED HOMOGENEOUS COATINGS

TABLE 3-3

HOMOGENEOUS COATING ELASTOMER COMPOUND
1969 AND 1977 REFERENCES

CONSTITUENTS	BOTTOM LAYER	CENTER LAYER	TOP LAYER
NEOPRENE W	100	-	-
POLYISOPRENE	-	100	-
FLOQUILL RR10	-	-	100
ZINC OXIDE	5	5	-
STEARIC ACID	2	1	-
MAGLITE M	4	-	-
NA - 22	0.75	-	-
NEOZON A	1.5	-	-
NEOPHAXA A	≈80	-	-
CIRCO LIGHT OIL	80	-	-
METHYL ZIMATE	-	0.25	-
SULPHUR	-	2	-
AGERITE WHITE	-	1	-
CARBON BLACK	-	2	-
DIBUTYL PHTHALATE	-	≈60	-
ALTAX	-	1	-

The second complete three-layer coating was described in the October 1977 Journal of ASNE. The same bottom layer was used, along with a thinner middle layer as shown on Figure 3-10. The outer layer wsa the plastic model-makers' Floquil paint of considerably greater thickness. The modulus of elasticity E = 10,000 psi is very high but an order of magnitude less than that of the butyrate dope previously used. The rubber compounds for the bottom layer and the middle layer are given by Table 3-3.

The Floquil RR10 elastic point is available in hobby shops and from the Floquil Company of Cobbleskil, NY 12043. The middle layer of the homogeneous compliant coatings is/was available from the Dental Manufacturing Company of Akron, Ohio 44310.

4 EXPERIMENTAL DATA

4. SUMMARY OF EXPERIMENTAL DATA

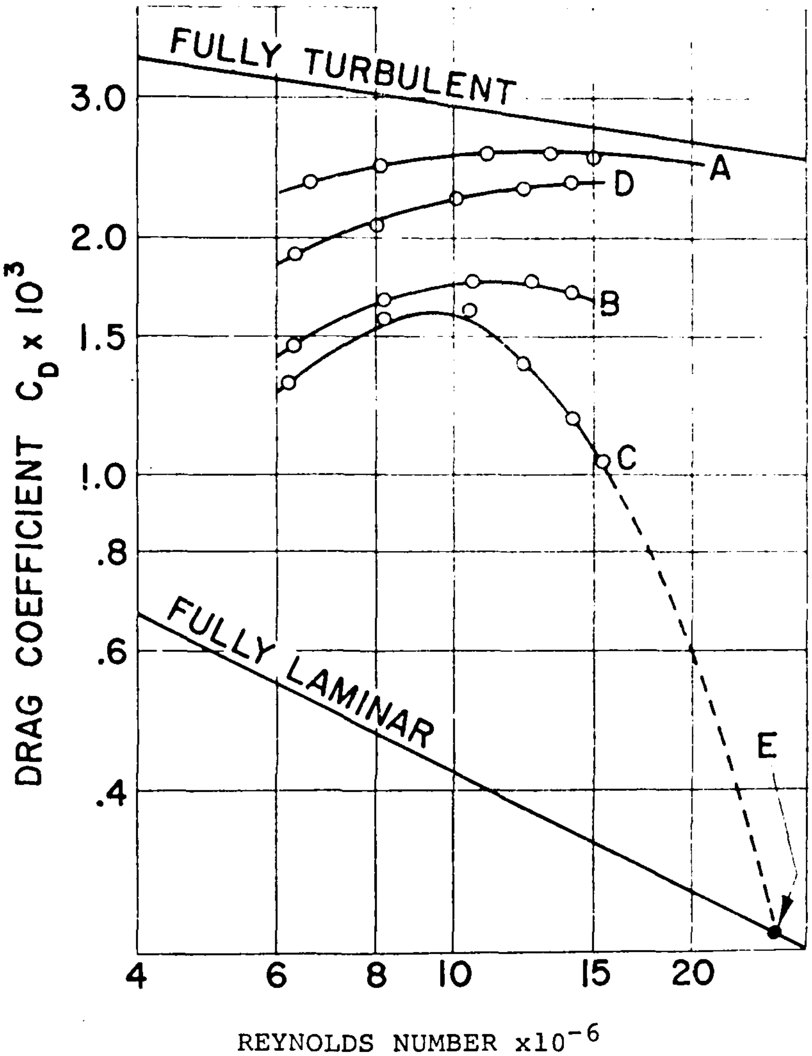
STUBBED COATINGS

The earliest experimental data available for Kramer's compliant coatings was published in The Journal of ASNE for February 1960. The twenty-one (21) data points shown on Figure 4-1 provide four curves, three of which had been optimized for the stiffness parameter. There might well have been an additional twenty data points acquired to carry out this reported suboptimization of late 1958, early 1959. These dates could be refined and additional data would be available from the final contract reports of the ONR sponsored research of 1958, 1959, and 1960 in a more detailed analysis.

Figure 4-1 presents drag or resistance coefficient data in the range $0.0010 \leq C_r \leq 0.0025$ for three suboptimized compliant coating models and for a rigid surface model all of the same geometry. The Reynolds number based upon the 114.3cm length of the test forebody is $6 \leq R_e x 10^{-6} \leq 15$. Note the importance of Kramer's stiffness parameter for a coating under compression which approximates Young's modulus, E. These data are for a stubbed coating, fluid filled with silicone at 15,000 centistokes.

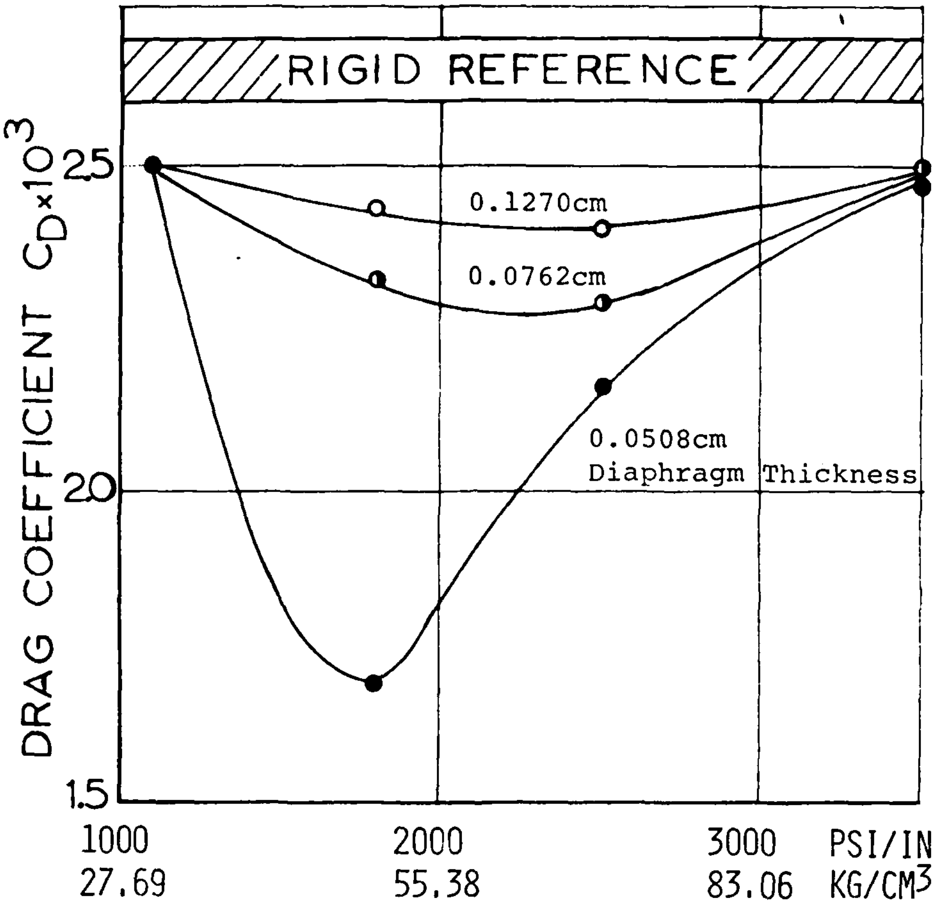
RIBBED COATINGS

The suboptimization of the stiffness parameter for ribbed compliant coatings is shown on Figure 4-2. Recall that the ribbed material along with the high viscosity fluid filler becomes the lower layer. Also shown there is the suboptimization for diaphragm thickness. The diaphragm thickness of 0.127cm was attained by summing an 0.1016cm ribbed coating diaphragm and an 0.0254cm outer diaphragm. The 0.0762cm total was attained by summing an 0.0508cm ribbed coating diaphragm and an 0.0254cm outer diaphragm. The 0.0508cm figure was provided by the ribbed coating diaphragm alone. Without tests at 0.0889cm and at 0.0635cm, one can only speculate where the maximum drag reduction would have occurred. These tests were conducted at 16.46 m/sec towing speed at a Reynolds number of $15x10^6$ with a fluid viscosity of 10,000 centistokes. The test body coating variations were on the 60.96cm portion of the cylinder The 30.48cm coating of the 0.0762cm diaphragm, 69.22 kg/cm^3 stiffness,



Rigid Reference Model, Curve A; Stubbed Coatings, E = 44.30 kg/cm3, Curve B; E = 22.15 kg/cm^3, Curve C; E = 16.61 kg/cm^3, Curve D; and E = 22.15 kg/cm^3, for Calculated Point E

FIGURE 4-1 DRAG COEFFICIENT VERSUS REYNOLDS NUMBER



COATING STIFFNESS

FOR υ = 16.46 m/sec; $R_e = 15 \times 10^6$; 10,000 centistokes

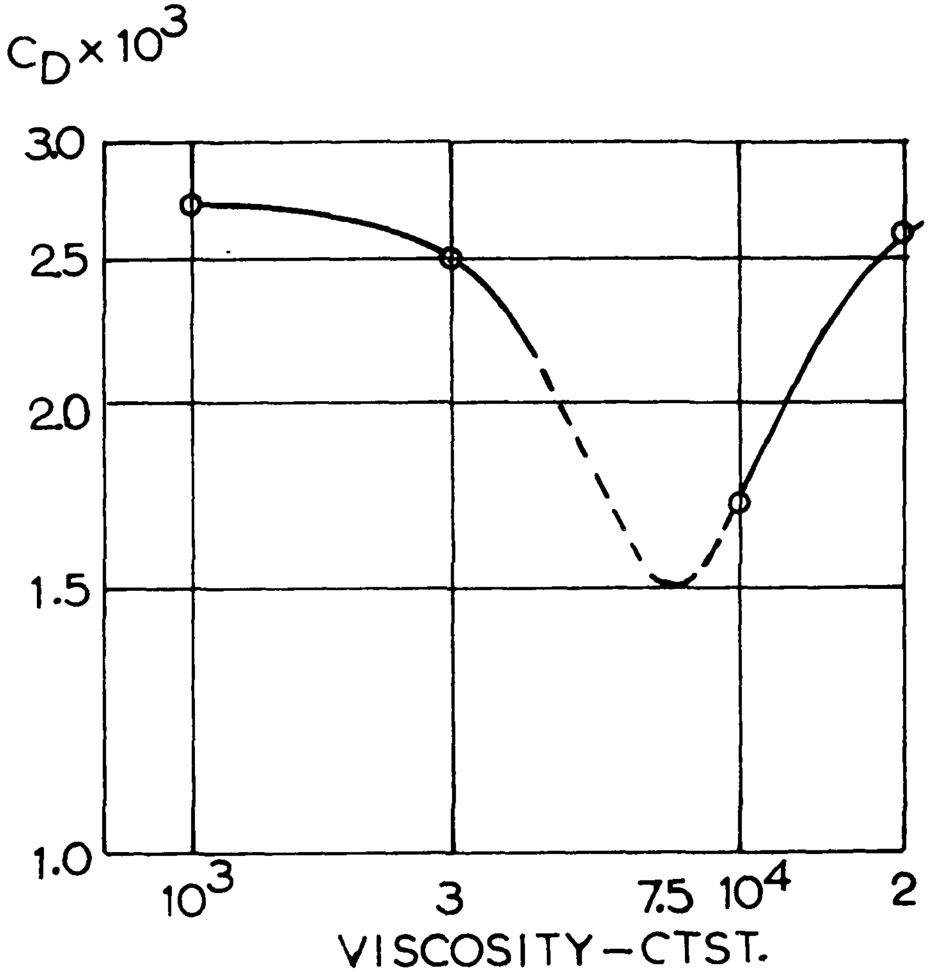
FIGURE 4-2 RIBBED COATING DRAG COEFFICIENT VERSUS STIFFNESS

and 10,000 centistokes on the ogival tip, was constant for all tests.

In turn, viscosity was suboptimized for the best of the three diaphragm thicknesses described above, i.e., the 0.0762cm thickness at 49.84 kg/cm^3 stiffness, at 16.46 m/sec and a Reynolds number of 15x10^{-6}. Figure 4-3 presents the experimental results at four values of fluid viscosity. The faired curve indicates the lowest drag would occur at about 7500 centistokes. Assuming that these experimental results provide reliable data for the separate suboptimizations, greater drag reductions may have resulted for combinations of the parameters which were not tested.

The Reynolds variation of the best of the ribbed coatings tested, i.e., 10,000 centistokes viscosity in the 61.0cm cylindrical length with 49.84 kg/cm^3 stiffness and a diaphragm thickness of 0.0762cm is shown on Figure 4-4 by the data points represented by circles. Based on a test body length of 114.3cm, the drag coefficient monotonically declines over the Reynolds number range of 8 to 19x10^{-6}. The interpolated lowest drag coefficient at 7500 centistokes on Figure 4-3 corresponds to the (hypothetical) double-dashed curve. The lowest curve drawn with single dashes is for the best of the stubbed coatings. This curve and the double-line curve at the top are taken from the February 1960 Journal of ASNE article. The dashed line drawn through data points represented by crosses shows the marked loss of effectiveness of the stubbed coating after storage for one year. The physical changes were discussed earlier under the heading of coating design.

With the receipt of specially compounded and molded rubber diaphragms from the Non-Metallic Materials Laboratory of Aeronautical Systems Division, WPAFB, new tests were run on diaphragm thickness. To a ribbed coating with a molded diaphragm thickness of 0.0381cm, replaceable diaphragms of 0.04572cm and of 0.09144cm were added. These diaphragms were molded from the potting compound LTV-602 by General Electric and from polyisoprene and polybutadiene compounds described in the coating design section. The coated portion of the cylindrical section was 30.5cm in length and fluid-filled with 8500 centistokes silicone. The test results



For v = 16.46 m/sec; E = 49.84 kg/cm^3;

Diaphragm Total Thickness 0.0762cm

FIGURE 4-3 DRAG COEFFICIENT OF BEST RIBBED COATING VERSUS FILLER FLUID VISCOSITY

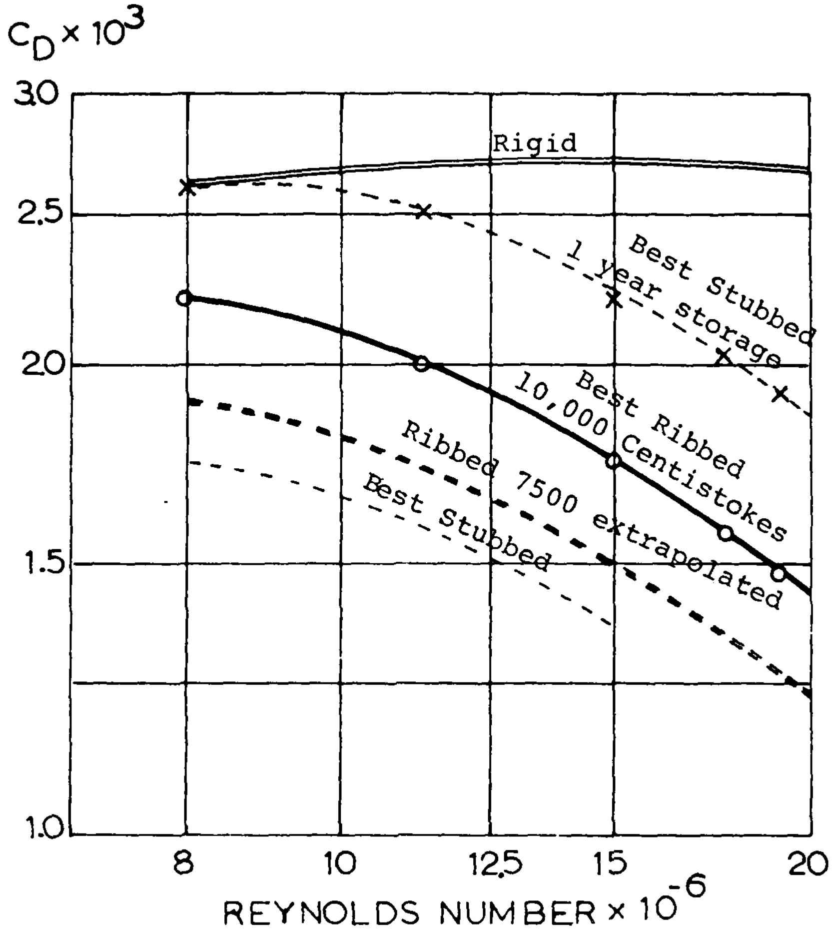


FIGURE 4-4 DRAG COEFFICIENT OF STUBBED AND RIBBED COATINGS VERSUS REYNOLDS NUMBER

presented on Figure 4-5 were obtained with the short 21.59cm rigid tip on the test body which was tested at 3^{o} angle of attack to insure laminar flow on the top back to the start of the coating. The results are useful only in comparison with the rigid body reference. For the lower set of three curves shown on Figure 4-5, the 0.04572cm outer diaphragm (0.08382cm total diaphragm thickness) coatings showed a reduction in drag of about 25 per cent for the polybutadiene and polyisoprene materials. The LTV-602 curve (not shown) was closer to the rigid body reference curve. The 0.09144cm outer diaphgram (0.12954cm total diaphragm thickness) curves (also not shown) were generally above the rigid body reference curve. The Reynolds numbers shown are lower than for previously cited results because a shorter model was used. The rigid tip was only 20.32cm long and the cylindrical portion was only 50.8cm long for a total length of 71.12cm vice 114.30cm. The maximum Reynolds number of 9.6×10^{6} corresponds to 16.46 m/sec.

The upper set of three curves shown on Figure 4-5 corresponds to the three curves discussed above, except that boundary layer trips were added 5.08cm aft of the tip of the rigid body. Fourteen wires of 0.1194cm diameter and 0.3175cm in length formed each boundary layer trip. At $R_e = 9.2 \times 10^{6}$, there is an 8.7 per cent reduction for both the polyisoprene and polybutadiene outer diaphragms of 0.04572cm thickness (0.08382cm total diaphragm thickness). Kramer reported this result in one of the unpublished RAND internal documents and promptly forgot it. He returned to the pursuit of extending laminar flow which will never be of consequence to a large submerged body.

In the same reference Kramer reported on the suboptimization of the silicone filler-fluid in the ribbed coating. He pursued the suboptimization of the polybutadiene outer diaphragm upward from the lower values of viscosity and the polyisoprene outer diaphragm downward from the high values of viscosity. The maximum reduction appears to result at about 12,000 centistokes, as shown on Figure 4-6. These tests were performed at 16.46 m/sec or $R_e = 9.2 \times 10^{6}$ with the 0.04572cm added outer diaphragm with 20.32cm rigid tip and a 30.48cm coating on the

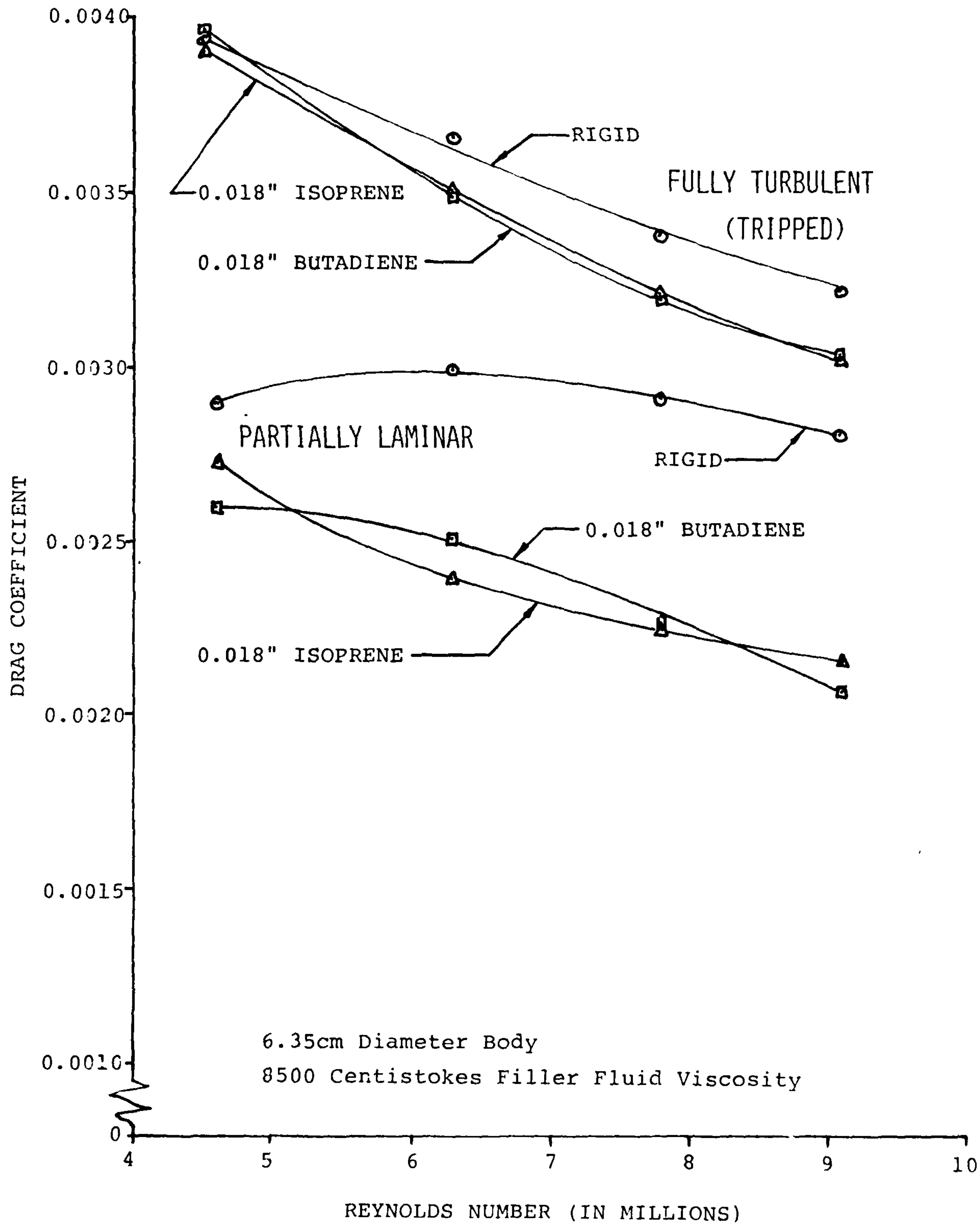


FIGURE 4-5 DRAG COEFFICIENT OF RIBBED COATING VERSUS REYNOLDS NUMBER

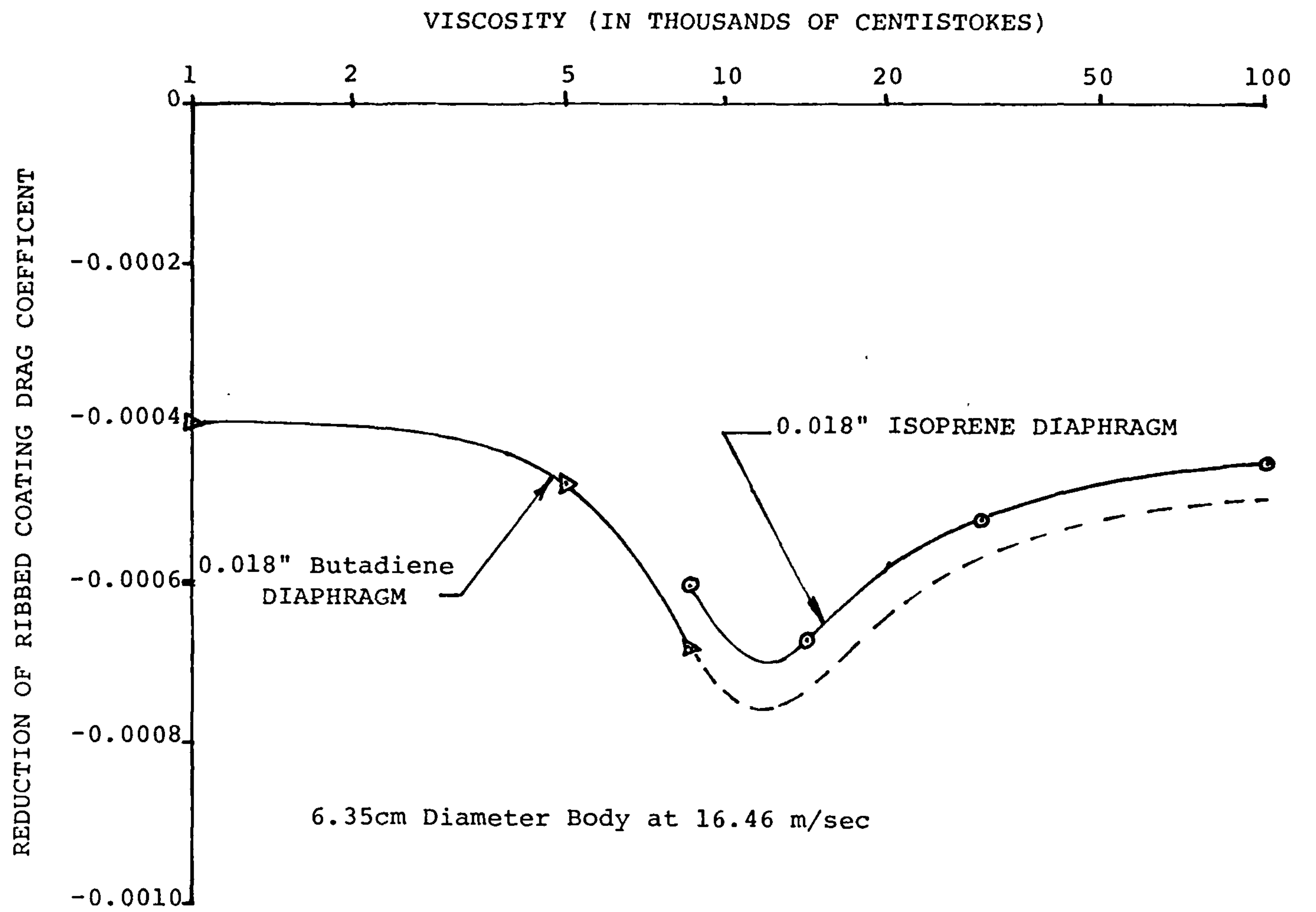


FIGURE 4-6 REDUCTION OF RIBBED COATING DRAG COEFFICIENT VERSUS FILLER FLUID VISCOSITY

50.80cm cylindrical length. The stiffness of the coating was not cited in the reference.

HOMOGENEOUS COATINGS

During late 1967 and early 1968 Kramer tested the second design of the buoyant or "pop-up" bodies in the Pacific Ocean offshore of Santa Monica. This machined thin-wall body was coated 58.42cm aft from the nose with the original homogeneous, three-l r compliant coating. This coating on the same body was made rigid by adding eighteen coats of butyrate dope to the outer layer to a thickness of 0.0127cm. This more expensive body was blown away on the surface by gusting winds and lost December 5, 1967. Additional tests were performed on the molded bodies for the same geometry in March 1968.

The results of the tests from an unpublished reference prepared by M.O. Kramer of April 1, 1968, are shown on Figure 4-7. The points for the lower line were from the "lost" machined body with a release depth of 32.00m, and all coatings included the multiple layered butyrate dope of 0.00254cm thickness. The homogeneous bottom layer thickness was 0.1016cm and the homogeneous middle layer thickness was 0.0508cm. The numbers beside the points indicate the number of test runs for which the results were averaged. This was done in response to earlier criticism of lack of repeatable results. The maximum difference for any of the points from its group's average was stated to be 6 per cent.

The points for the upper line were obtained with the two molded bodies with and without the original homogeneous compliant coating. Note that the (five) rigid coating data points fall along the same line as the data point for the compliant coating model with boundary layer trip and as the (two) data points for compliant coating. There was no thin outer layer of butyrate dope on any of these test bodies and they seem to act as rigid coatings. At 18 m/sec, there is a drag reduction of about 48 per cent when the third, outer layer of the coating is added. Note that the drag for these tests was reported as "flat plate drag" or $A_w \times C_r$, which subsonic aerodynamicists used. It is obviously dependent

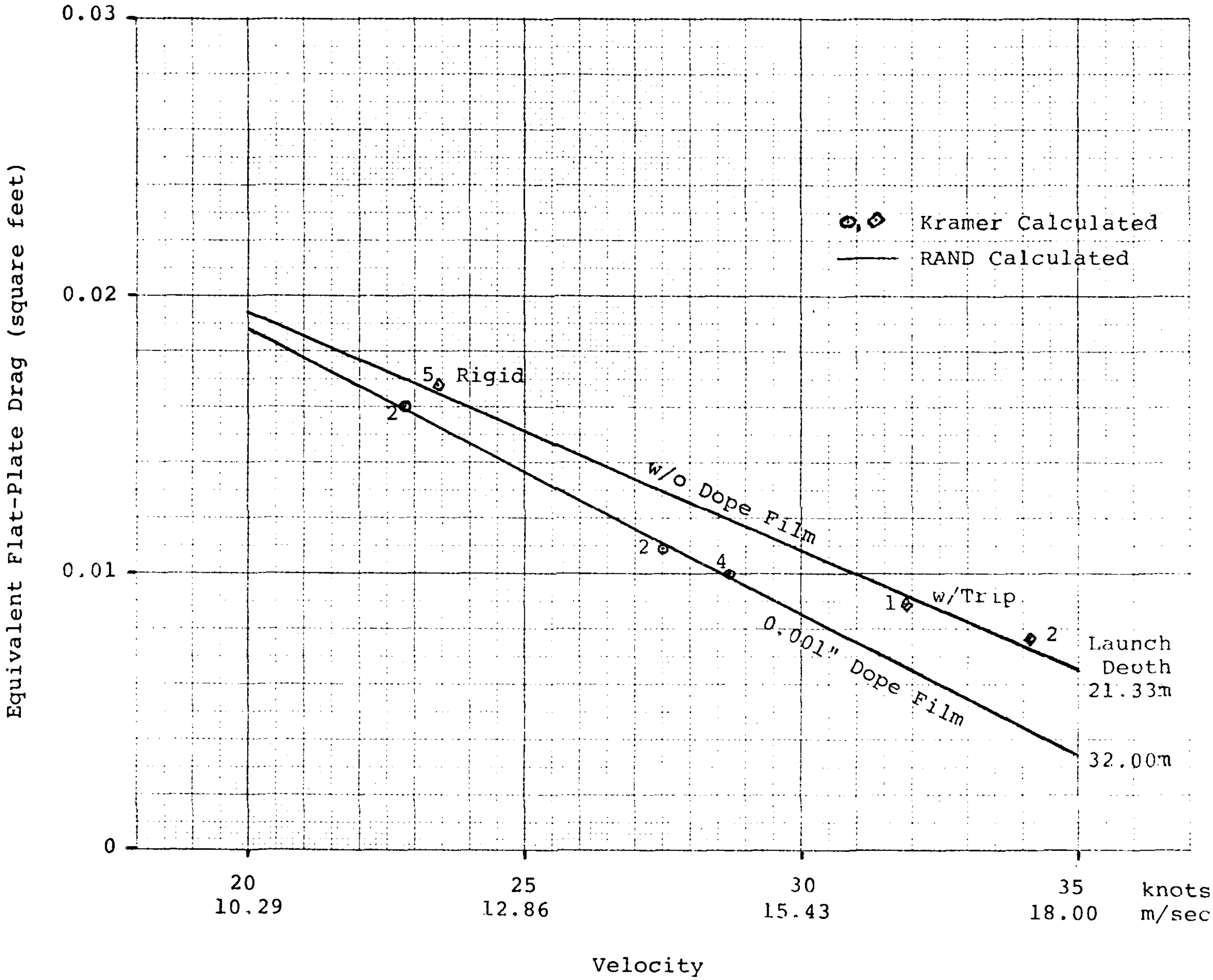


FIGURE 4-7 BUOYANT BODY FLAT-PLATE DRAG VERSUS VELOCITY

upon the size of the body and is not a true coefficient.

Another unpublished reference prepared by M.O. Kramer in March 1969 presented data for three-layer homogeneous coating of 76.20cm length on the 129.54cm molded Reichardt-shaped bodies with and without boundary trips. As shown on Figure 4-8, this showed only a small reduction in length of laminar flow and a slight increase in drag area ($A_w \times C_r$), from 11.05cm^2 to 11.984cm^2. This is the third time Kramer mentioned this recovery of laminar flow after a serious disturbance. The coated model drag, as reported, is about 28 per cent less than that for the rigid model. Earlier test results reported for this coated test body were based upon a coating length of 58.42cm. This reference stated that the coating was cut and affixed in three longitudinal sections of 120^o each around the periphery. The manual skill and practical knowledge in the preparation of the test bodies has been obvious throughout this review and this task merely reinforces that point.

The published, but difficult to obtain, article by Kramer in 1969 Jahrbuch Deutschen Gesellshaft fur Luft-und Raumfahrt touches on his earlier experiments with stubbed and ribbed coatings. Figure 4-1 of this review is repeated, but the curves are identified in terms of tensile modulus, M. In Section 3 on compliant coating design, the optimization of the damping was hinted at, but no data were presented. This 1969 article for which a translation has not yet been obtained, does present drag coefficient data versus a damping ratio for polyisoprene diaphragms. The base case became the middle layer of the three-layer homogeneous compliant coating. In addition, there is plot of drag coefficient versus viscosity with seven data points versus the four data points of Figure 4-3. At a 15 per cent lower speed of 13.89 m/sec, the faired curve is about 20 per cent lower. That implies further improvement because reduced speed and Reynolds number usually increased, i.e., lessened the reduction.

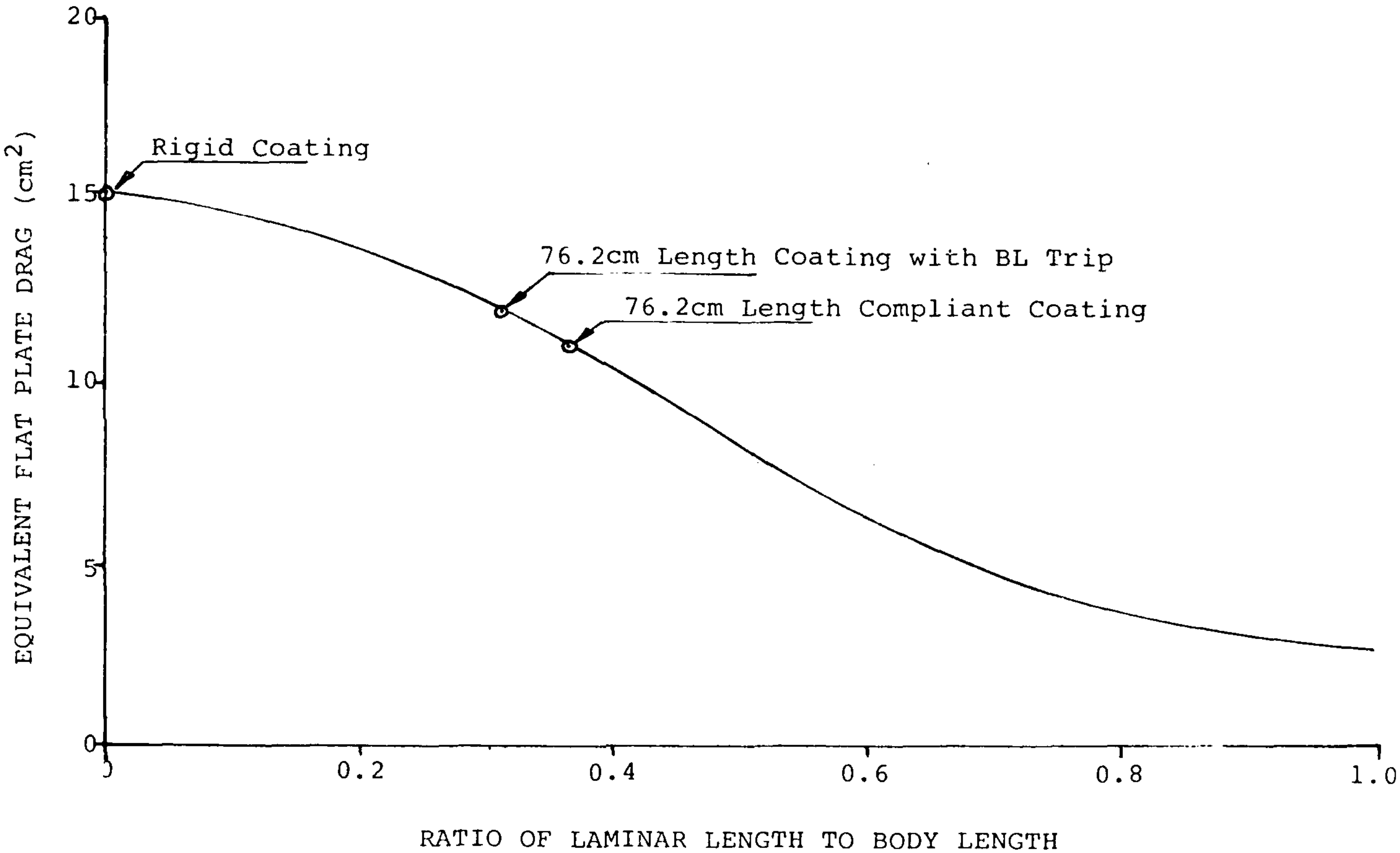


FIGURE 4-8 EQUIVALENT FLAT PLATE DRAG AREA VERSUS LENGTH RATIO

The reporting on the then new three layer homogeneous coating was indirect in that no drag coefficient data was shown. However, the increases in transition Reynolds number versus test speed was presented for the old ribbed coating, for the two homogeneous layers, and for the homogeneous layers. The 0.0006cm outer layer, in this instance, was DuPont mylar film having a tensile modulus, M = 28,000 kp/cm^2. These data are presented on Figure 4-9.

IMPROVED HOMOGENEOUS COATING

The final years of research (1969 - 1975) are less completely documented, because Kramer returned to Germany for "several" years and because he was afflicted with a series of minor strokes, (circa 1974 - 1978) after his return. The capstone to his 19 years of experimental research with compliant coatings was reported in the October 1977 Journal of ASNE. This three-layer homogeneous coating had the same bottom layer of 0.1016cm thickness as the original three-layer homogeneous coating, but a thinner middle layer of 0.03556cm. The extremely resiliant butyrate dope and mylar films tested as the third layer of the original homogeneous coating was replaced by a thicker elastic paint of high resiliancy.

The rigid surface drag coefficient data for the Dolphin-shaped body are presented versus Reynolds number in the range of 10-15x10^{-6} on Figure 4-10. Also shown there are two curves from Aerodynamic Drag, a book by Sighard F. Hoerner.

In this same range $10 \leq R_e x10^{-6} \leq 15$, the drag coefficient data for the improved homogeneous compliant coating is shown on Figure 4-11. The open circle symbols correspond to test data with butyrate dope as the very high resiliancy outer layer. The closed circle symbols correspond to test data with Floquil RR10 elastic paint as the high resiliancy outer layer. Note that the drag coefficient is still declining for the latter coating at 16.5x10^{-6} Reynolds number.

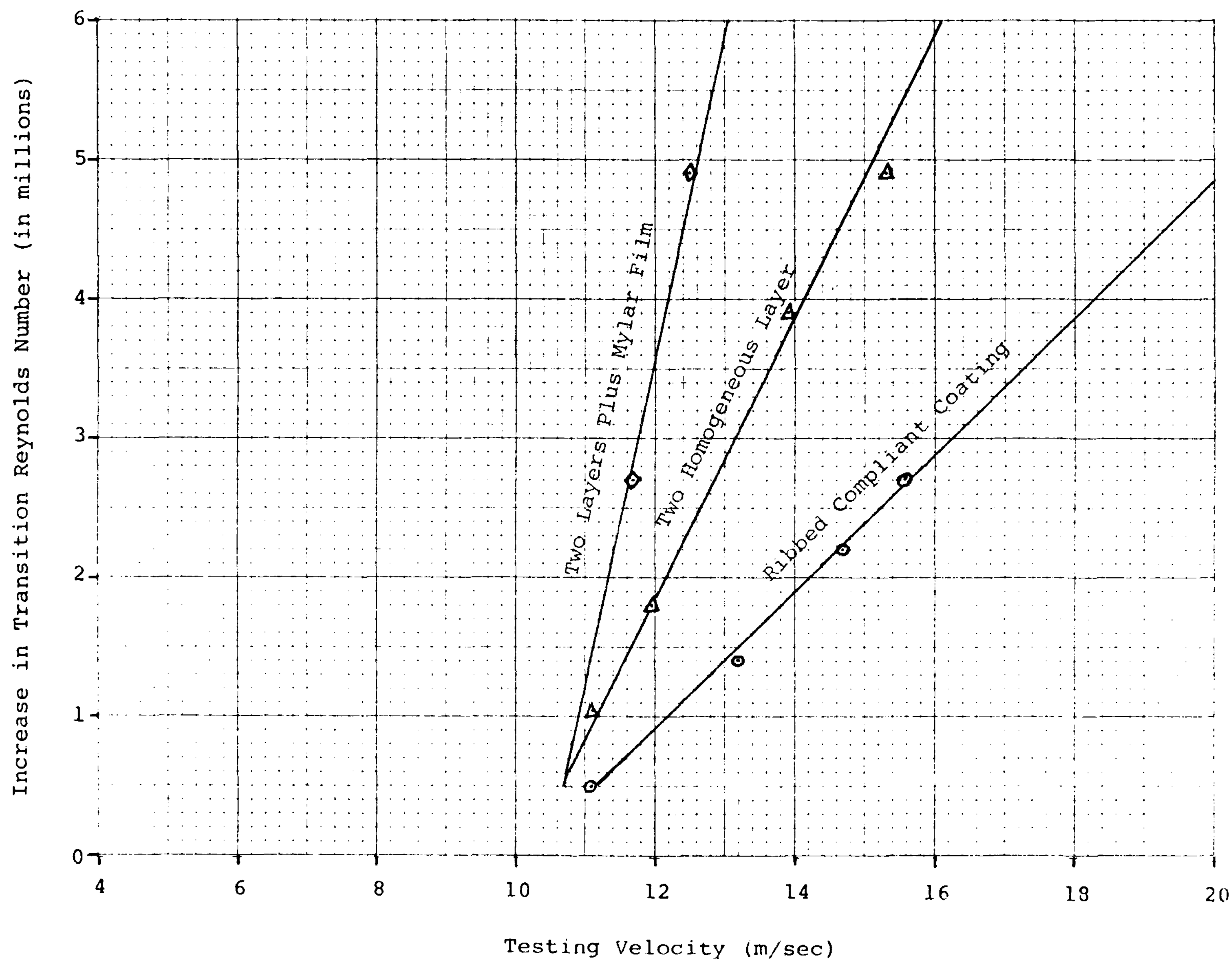


FIGURE 4-9 TRANSITION REYNOLDS NUMBER INCREASE VERSUS TEST VELOCITY

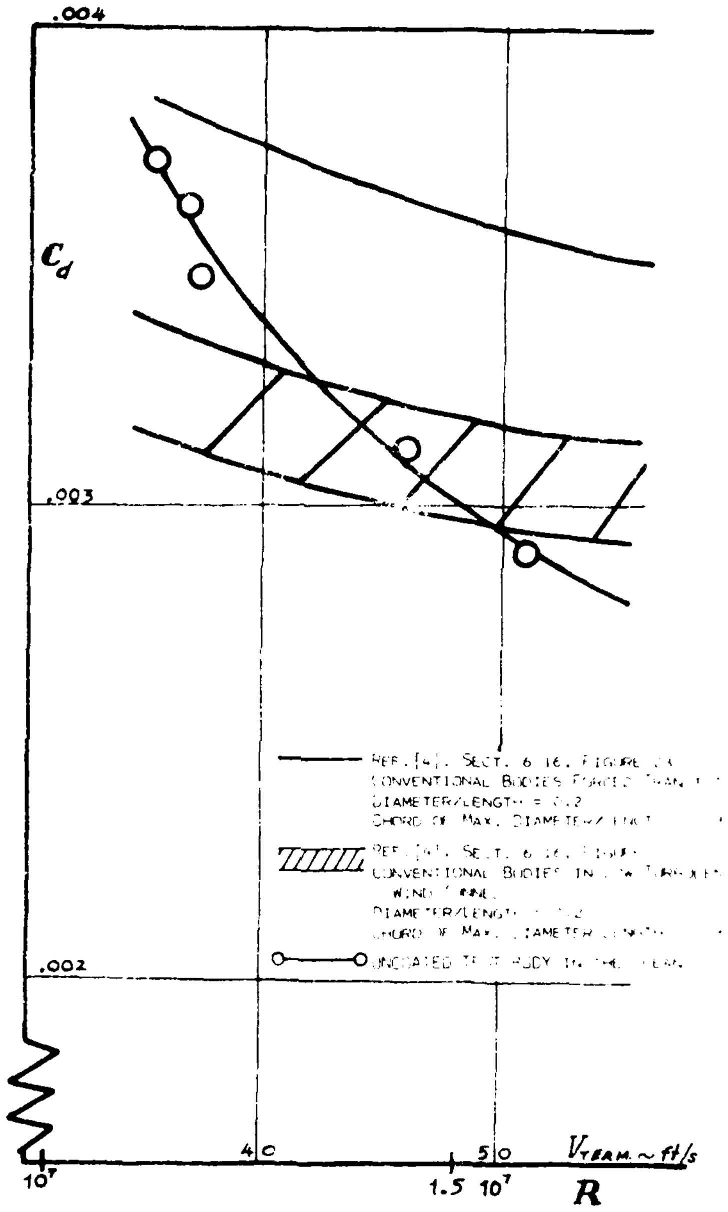


FIGURE 4-10 RIGID SURFACE DRAG COEFFICIENT VERSUS REYNOLDS NUMBER

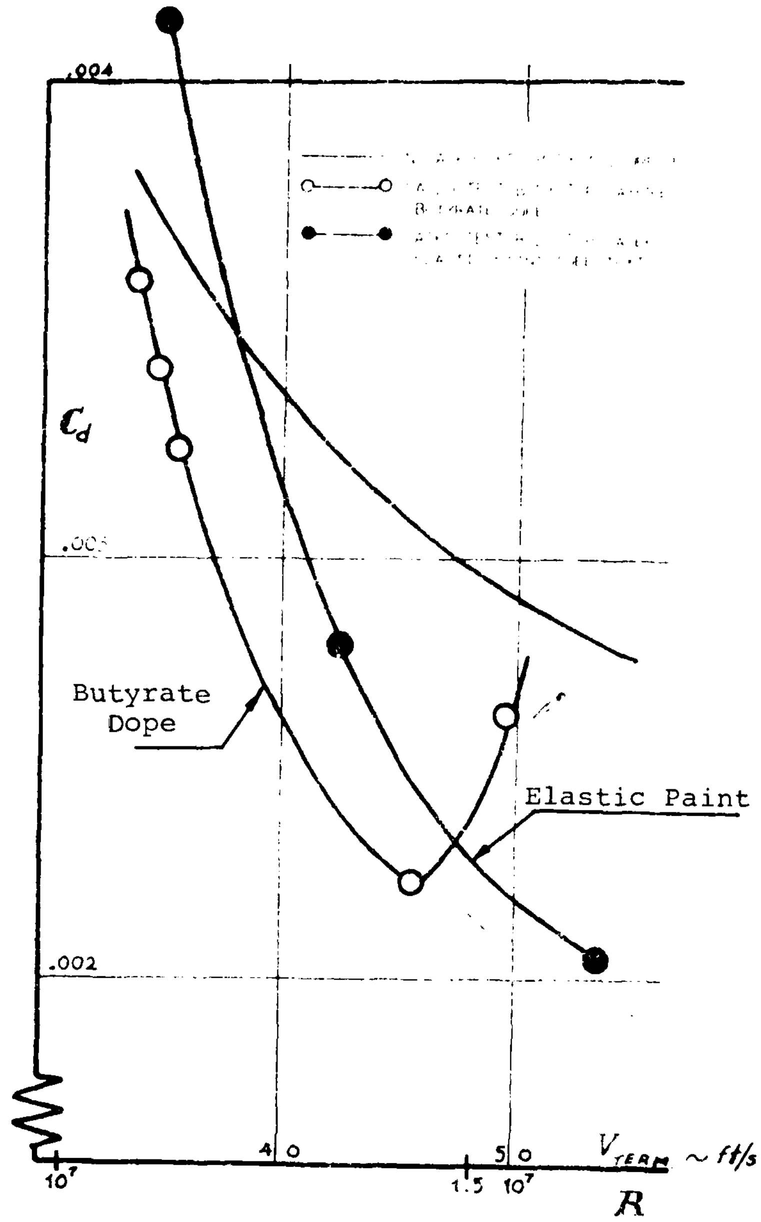


FIGURE 4-11 THREE-LAYER HOMOGENEOUS COATING DRAG COEFFICIENT VERSUS REYNOLDS NUMBER

5 EVALUATION

5. EVALUATION OF EXPERIMENTAL RESULTS

The consistency of the experimental results for compliant coatings relative to rigid coatings under the same conditions for literally hundreds of tests is apparent to the serious reader. The consistency of the three goups of relative results for the three different test techniques is impressive to the layman.

The suboptimization of fluid-filler viscosity, of compliant coating stiffness, of "diaphragm" (middle layer thickness), and of the very high resiliance, low damping outer layer were measured and reported in absolute value and each time compared with test results for the rigid surface. Discernible variations of the experimental results for these individual parameter suboptimizations lead to combined parameter optimizations with greater drag reductions reported. The rather subtle suboptimization of filler-fluid viscosity with one diaphragm material from the lower side, with comparable results for a second diaphragm material from the higher side is an impressive example of repeatibility by the original investigator.

The original investigator was highly motivated and apparently produced good experimental results in an area of research of small interest to practical applications. However, if these results obtained in the transition region between laminar and turbulent flow are properly parameterized according to the refined scientific investigations within the boundary layer, the two efforts may be combined for productive results. The real problem area for practical applications is in skin friction reduction for the turbulent boundary layer.

The acceptance of the experimental results by the original investigator is not granted by the scientific community in 1980, for the same reasons that it was not granted in 1960. The rigorous standards of scientific investigation were not met, and the gradual improvements by the investigator to meet these standards were not adequate. The standards of the scientific community are very expensive, but these costs are greatly diluted by the many hours contributed by the faculty advisors to, and the candidates for, the doctoral programs. Without

such financial support, the original investigator attacked a vast new field with inadequate funding and without guidance from a developed and accepted theoretical base.

The missing link(s) would be to perform a detailed error analysis of each of the three experimental techniques used by the original investigator. These non-trivial analyses would require substantial effort and funds, even if all the specific details were available.

In a more practical sense, the best, final results of the original investigator should be subjected to validation by qualified independent investigators, with scientific control to duplicate the test conditions.

If these experiments validate the overall results, the much more refined investigations of the parameters, and their suboptimizations will be warranted.

APPENDICES

APPENDIX A

BIOGRAPHY OF DR. MAX O. KRAMER

1961

PROFESSIONAL EXPERIENCE

April 1958 to December 1960:

Vice-President and Director of Coleman-Kramer, Inc.

Coleman-Kramer, Inc., Los Angeles, was a research laboratory that developed my invention called, "Boundary Layer Stabilization by Distributed Damping." My latest publication in this field is contained in the February, 1960 issue of The Journal of the American Society of Naval Engineers, Inc., a reprint of which is enclosed.

Coleman-Kramer, Inc. was jointly financed by the Coleman Engineering Company, Inc. of Torrance, California and the United States Rubber Company, New York. The latter company had received an exclusive manufacturing license on all products resulting from the Coleman-Kramer, Inc. research (reference enclosed copy January 1960 Press Release of U. S. Rubber Co.). At the end of 1960, following three years of jointly financed research, the United States Rubber Company decided that they had been taught enough about the new field to proceed on their own. Thus, they did not renew their support agreement with Coleman-Kramer for the present year, 1961. Since Coleman Engineering Company could not support the research on its own, the events led to the termination of the Coleman-Kramer activity.

July 1953 to March 1958:

Director of Coleman Engineering Company, Inc., Torrance, California, supervising several research projects, such as the development of a supersonic acoustic homer for the terminal guidance of small fighter-borne rockets under contract with the U. S. Navy; turbulence studies in the wake of aircraft targets under contract with the U. S. Air Force; and preliminary studies on the principle of "Boundary Layer Stabilization by Distributed Damping."

September 1946 to June 1952:

Consultant at the Naval Air Development Center, Johnsville, Pennsylvania, consulting on several guided missile projects and investigating the preliminaries of a supersonic acoustic homer for the terminal guidance of small fighter-borne rockets.

April 1943 to October 1945:

Head of the Guided Missile Development Station at Ruhrstahl, Brackwede, Germany, employing 300 and developing the "X-4", a small fighter-borne rocket which was patterned after my previous development of a 3,000-lbs. armor-piercing guided bomb, the "Fritz-X". The "X-4" passed all official proving ground tests and was scheduled for mass production at the end of 1944.

January 1932 to March 1943:

Employee of the German Research Center for Aeronautics, Berlin, Germany, from 1932 to 1935 I developed the first large-size low-turbulence wind tunnel (1932 - 1935); while heading this tunnel, I and Dr. Doetsch developed the first German laminar profile (1935 - 1936); thereafter I headed the Aerodynamic Institute (1936-1938), developed the first successful German guided missile, the "Fritz-X" (1939-1942); and studied the possibilities of a small fighter-borne rocket which, later, was to become the "X-4" (1943-1943).

SCIENTIFIC PUBLICATIONS IN ENGLISH LANGUAGE*

"The Dolphins' Secret"
THE NEW SCIENTIST, London, Vol. 7, No. 181, pp. 1118-20. 5 May 1960.

"Boundary Layer Stabilization by Distributed Damping"
The JOURNAL of the AMERICAN SOCIETY of NAVAL ENGINEERS, Inc., pp. 25 - 33, February, 1960.

"Boundary Layer Stabilization by Distributed Damping"
JOURNAL of the AERO/SPACE SCIENCES, Vol. 27, No. 1, pp. 69, January, 1960.

"Boundary Layer Stabilization by Distributed Damping"
JOURNAL of the AERONAUTICAL SCIENCES, Vol. 24, No. 6 pp. 459-60, June, 1957.

"Turbulence Measurements in Flight"
JOURNAL of the AERONAUTICAL SCIENCES, Vol. 20, No. 9 pp. 655-56, September, 1953.

"The Aerodynamic Profile as Acoustic Noise Generator"
JOURNAL of the AERONAUTICAL SCIENCES, Vol. 20, No. 4 pp. 280-282, 296, April, 1953.

"The Wave Drag of Ships"
JOURNAL of the AMERICAN SOCIETY of NAVAL ENGINEERS Inc., Vol. 62, No. 3, pp. 575-582, August, 1951.

"The German Guided Missile X-4" (Project No. NTE-63--Max Kramer)
SUMMARY REPORT NO. F-SU-2131-ND by F. E. Patton, released June, 1947 from Headquarters, Air Materiel Command, Wright Field, Dayton, Ohio. (ABSTRACT: "Summarizes available data on German Guided Missile X-4 with details of control, radio, airframe, propulsion, production, laboratory calculations and experiments. It was considered Germany's most effective air-to-air controlled missile especially against bomber formations. History of Dr.-Ing. Max Kramer, chief designer, is recorded as well as other personnel connected with the X-4 project. Report covers specifications, performance data, warhead and fuse and launching devices in considerable detail. Profusely illustrated and with adequate bibliography report is of value in guided missile research.")

*Does not include innumerable internal reports for Military and Company, nor German language publications.

"Remote Controlled Dive Bombs" (Ferngelenkte Sturzbomben - Max Kramer) English AAF TRANSLATION NO. F-TS-551-RE prepared 22 March 1946 for Intelligence (T-2) Air Documents Division Translation (Captured Document) Released by Headquarters, Air Technical Services Command, Wright Field, Dayton, Ohio, 29 April 1946.

EDUCATIONAL BACKGROUND

August 1929 to January 1932:

Received my Doctor of Science Degree at the Technical College, Aachen, Germany while working at the Aerodynamic Institute of Professor T. H. von Karman.

April 1922 to April 1926:

Received my Diploma in Electronics after three semesters at the University of Heidelberg and five semesters at the Technical College Munich, Germany.

BIOGRAPHICAL DATA

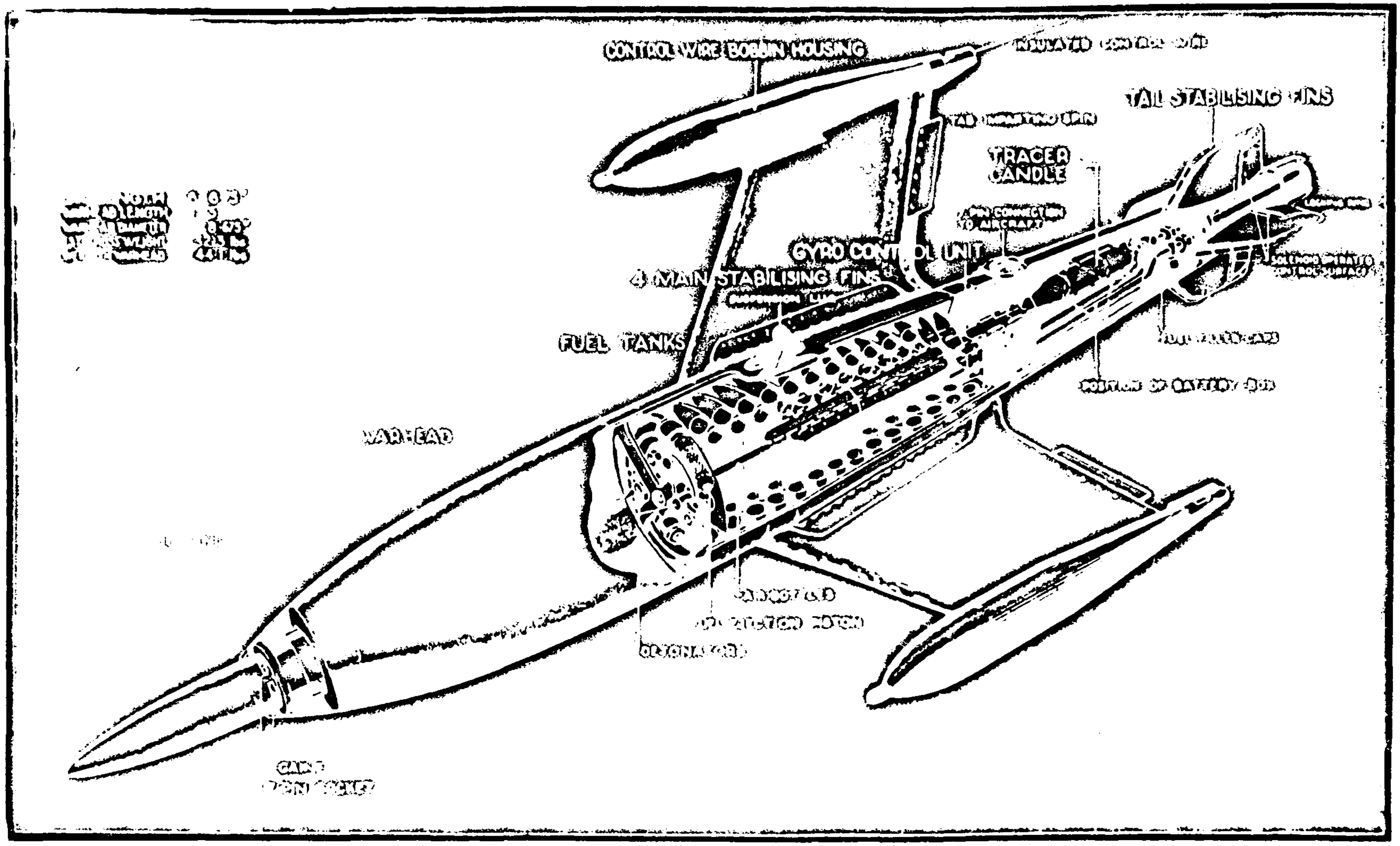
Born September 8, 1903, in Koeln, Germany.

Married September 29, 1934, in Berlin, Germany.

CITIZENSHIP

Received United States Citizenship in April, 1953.

(Note: Immigrated to United States in 1946 under U. S. Military Services "Project Paper-clip.")



Cutaway Drawing of X-4 Missile

APPENDIX B

CHALLENGES EXPRESSED BY SCIENTIFIC COMMUNITY

- FEBRUARY 1962 PROFESSOR E. COVERT IN MIT MEMO: GOT THE IMPRESSION THAT PROFESSOR LANDAHL THINKS MOK'S RESULTS ARE REAL, BUT NOT FULLY UNDERSTOOD BY ANYONE, INCLUDING MOK
  - A DETAILED DISCUSSION BY MOK WOULD BE MISLEADING AT BEST
- FEBRUARY 1962 PROFESSOR D. COLES IN RAND MEMO:
  - DOLPHIN LOW DRAG NOT PROVED
  - MOK ACQUIRED INTEREST IN VALID PROBLEM FOR INVALID REASONS
  - B L SECONDARY INSTABILITY TO HIGH Hz DISTURBANCES DIFFICULT TO ASSESS
  - TIME HAS PROBABLY COME FOR MORE SCIENCE AND LESS ENGINEERING
  - DETAILED AND SOPHISTICATED PROGRAM OF THEORETICAL AND EXPERIMENTAL RESEARCH MUST BE VERY CAREFULLY PLANNED
  - SUGGESTED RESEARCH CENTERS AT CALTECH, JPL, NBS, JOHNS HOPKINS, CORNELL, AND CAMBRIDGE

FIGURE B-1 COMMENTS FROM MIT AND CALTECH

- OCTOBER 1962 PROFESSOR M. LANDAHL IN LETTER TO MOK
  - ML'S THEORETICAL INVESTIGATION PROMPTED BY MOK'S PIONEERING EXPERIMENTS
  - ADMIRED MOK'S SKILL IN OBTAINING SIGNIFICANT RESULTS USING VERY SIMPLE EQUIPMENT
  - INSTABILITY WAVES ARE ENERGY DEFICIENT
  - DAMPING WILL HAVE OPPOSITE EFFECT OF THAT IN AN ORDINARY MECHANICAL SYSTEM
  - ONE CANNOT RULE OUT ALTOGETHER THE POSSIBILITY THAT THE FLEXIBLE SKIN COULD HAVE AN INFLUENCE ON THE TURBULENT B L
- SPRING 1964 PROFESSOR J. COLE/BROOKE BENJAMIN CORRESPONDENCE
  - TO ENCOURAGE MULTIPLE-LAYERED COATING
  - THEORETICAL INVESTIGATION BY BB
  - INDEPENDENT TESTING BY DAVIDSON LABORATORY SPONSORED BY RAND TO PROVIDE CONVINCING DATA

FIGURE B-2 CORRESPONDENCE FOR INCREASED ACCEPTANCE

- PROFESSOR AF CHARWAT OBSERVED A POP-UP BODY LAUNCH:
  - EXPERIMENTAL TECHNIQUE CONCEPTUALLY VALID
  - EXECUTION IS UNJUSTIFIABLY POOR AND PRIMITIVE
  - CREDIBILITY OF RESULTS DRASTICALLY REDUCED
  - IF ENOUGH TESTS ARE CONDUCTED, RESULTS COULD BE STATISTICALLY VALID
  - A CLEAN EXPERIMENT CAN BE DEVISED WITH NOT MUCH MORE EFFORT AND EXPENSE
  - IMPORTANT TO DETERMINE THE DOMAIN OF EFFECTIVENESS OF OF DRAG REDUCTION COATING AS LIMITED BY AMBIENT TURBULENCE AND VIBRATIONS

FIGURE B-3 COMMENTS ON BUOYANT BODY EXPERIMENT

APPENDIX C
SUPPLEMENTARY INFORMATION

- PROFESSOR JOHN L. LUMLEY VISITED RAND 2 JULY 1964
  OFFERED TO TEST FLAT PLATE IN SMALL WATER TUNNEL
- M.O. KRAMER WROTE 6 JULY 1964 WITH QUESTIONS ABOUT
  TUNNEL AND PLATE PREPARATION
- J. AROESTY MEMO AT RAND, 8 AUGUST 1964 FROM TELECON WITH LUMLEY
  TESTS PERFORMED ON US RUBBER COATINGS : INEFFECTIVE ON TRANSITION
  MASTER'S DEGREE CANDIDATE TO TEST NEW US RUBBER AND KRAMER COATING
  RAISED QUESTIONS OF NEED FOR A SCHUBAUER, A LAUPER, OR A KLEBENOFF
- LUMLEY LETTER TO KRAMER 12 AUGUST 1964
  12"x12" PLATE; V_{MAX} = 75FT/SEC; V_{TEST} = 45FT/SEC
  SUCTION SLOT NEAR LEADING EDGE; PLATE ANGLE ADJUSTING

FIGURE C-1 FLAT PLATE TEST PLANNED FOR PENN STATE

- KRAMER LETTER TO LUMLEY, 28 AUGUST 9164
  - MUNTZ METAL PLATE TOO HEAVY (27LB)
  - SELECTED LINEN PHENOLIC WITH 16 BRASS PLUGS
  - TO ATTACH TO FIXTURE; DRAWING SKD 50995
- KRAMER MEMO TO RPJ, 25 SEPTEMBER 1964
  - LUMLEY RECEIVED RAND/KRAMER COATED PLATE
  - PRELIMINARY TEST PLANNED IN 1-2 WEEKS
- KRAMER MEMO AT RAND 13 NOVEMBER 1964, RE J.L. LUMLEY
  - TEST EQUIPMENT NOT READY PER TELECON 9 OCTOBER
  - REDESIGNED TEST EQUIPMENT PER TELECON 23 OCTOBER
  - SUCTION SLOT NOW CAUSING TRANSITION PER TELECON 6 NOVEMBER
- LUMLEY TO KRAMER LETTER 8 JANUARY 1965
  - 0.12% TURBULENCE OF TUNNEL TOO HIGH FOR SCHUBAUER-SKRAMSTAD
  - 0.03% ATTAINABLE WITH 1/32" HONEYCOMB NOW ON ORDER
  - RAND/KRAMER PLATE PLACED IN STORAGE; INDEFINITE DELAY

FIGURE C-2 TEST SPECIMEN PREPARED, TESTS DELAYED

- MO KRAMER CALLED PETER WARD BROWN   12 MARCH 1965
- RPJ LETTER TO PETER WARD BROWN   29 MARCH 1965
  - OUTLINE OF TEST PROGRAM
  - REQUEST FOR PROPOSAL
- PETER WARD BROWN CALLED RPJ 14 APRIL 1965 WITH QUESTIONS
- KRAMER LETTER TO BROWN 16 APRIL 1965 WITH ANSWERS
- P WARD BROWN LETTER TO RPJ WITH PRELIMINARY COSTS, 26 APRIL 1965
- RAND WORK STATEMENT, 7 MAY 1965
- EARL URAM LETTER TO MOK, SHOP WORK COMPLETE BY 27 AUGUST
  INITIAL TANK OPERATION ON 31 AUGUST, DATED 23 AUGUST 1965

FIGURE C-3 DAVIDSON LABORATORY TESTS PLANNED

- E URAM TELECON RPJ, 28 SEPTEMBER 1965
    - INVITED KRAMER FOR OCTOBER 7,8, TESTS
    - (49 RUNS ALREADY; RIGID MODEL BLISTERED; NEITHER REPORTED AT TIME)
- KRAMER DEBRIEF AT 11 OCTOBER 1965
    - NO YAW ANGLE MEASUREMENT
    - ANGLE OF ATTACK MEASURED
    - STRAIN GAUGE REPLACED
    - AMBIENT TURBULENCE LOW ON INITIAL RUN
    - OVERNIGHT IN DRYDOCK WATER: COATING BLISTERED
    - 60 FT/SEC RUN BENT STRUT, DISENGAGED CARRIAGE
    - VIOLENT LONGITUDINAL VIBRATIONS AT 10-15 Hz
    - DRAG VARIATIONS OF ±10%
- KRAMER MEMO TO RPJ 19 OCTOBER 1965
    - DETAILED REVIEW OF 11 OCTOBER TELECON REMARKS

FIGURE C-4 DAVIDSON TEST RUNS AND PROBLEMS

- DAVIDSON LABORATORY LETTER OF 5 NOVEMBER 1965 TO RPJ RESIDENCE TRANSMITTING:
  - (2) TANK 3 DATA SHEETS
  - (2) CALCULATION SHEETS
  - (7) ROUGH PLOTS
  - (1) ORIGINAL VISICORDER TAPE OF DATA
  - RPJ RETURNED VISICORDER TAPE 11 NOVEMBER
- OVERRUN FUNDING REQUESTED (STRAIN GAUGE REPLACEMENT AND TROUBLE SHOOTING AFTER RUNS 46-49), 8 NOVEMBER 1965
- RPJ TO HOWARD OREM (DIRECTOR OF RESEARCH), 17 NOVEMBER 1965
  - FUNDS EXPENDED BUT OBJECTIVES NOT MET
  - LONGITUDINAL VIBRATIONS UNACCEPTABLE
  - MISALIGNMENT OF VERTICAL TOWING STRUT TERMINATED TESTS WITH MOK PRESENT AS OBSERVER

FIGURE C-5 RAND/KRAMER QUESTIONS OF TEST CONDITIONS

- HW McDONALD (DEPUTY DIRECTOR) LETTER TO RPJ, 9 DECEMBER 1965
  - MOK SATISFIED WITH FACILITY, RECOMMENDED SHOCK MOUNTS
  - (MONORAIL CARRIAGE SWAY A CONCERN OF MOK)
  - 2 Hz NATURAL FREQUENCY OF TOWING CABLE-CARRIAGE SYSTEM
  - 120-150 Hz FREQUENCY OF CARRIAGE WHEELS
  - 12-15 Hz MAYBE NATURAL FREQUENCY OF INTEGRATED MODEL AND SUPPORT STRUCTURE
  - DIFFERENTIAL PRESSURE TRANSDUCER CAREFULLY CALIBRATED
  - HYDRODYNAMIC INSTABILITY IN YAW, NOT STRUT ALIGNMENT BLAMED FOR BENDING OF STRUT
  - (45) RUNS MADE IN PRESENCE OF MOK, 6-8 OCTOBER 1965
- MOK REBUTTAL LETTER TO RPJ, 14 DECEMBER 1965
  - FRUITLESS TO ARGUE AGAINST INCORRECT CLAIMS OF AGREEMENT
  - LONGITUDINAL VIBRATIONS DEDUCED AS CAUSE OF NO DRAG REDUCTION
  - VISICORDER TAPE REVIEW CONFIRMED 12-15 Hz LONGITUDINAL
  - TOWING STRUT TOO STIFF TO BEND

FIGURE C-6 DISCLAIMER OF RESPONSIBILITY AND REBUTTAL

- JS KING (TREASURER) LETTER TO HOWARD OREM 3 FEBRUARY 1966
  - 75 PER CENT OF FUNDS EXPENDED BY 30 SEPTEMBER
  - $20 STRAIN GUAGE AND 1 MAN-DAY INSTALLATION APPROVED BY MOK AS HE WOULD ACCOMPLISH REPLACEMENT-NOT EVENTUAL $1200 OVERRUN REQUESTED
  - CONTRACT CALLED FOR 35 TEST RUNS TOTAL AT 3 PER WEEK, BUT 49 RUN BEFORE MOK INVITED
  - PRESSURE TRANSDUCER MALFUNCTION DURING SERIES AND STRAIN GAUGE FAILED FOR #46-#49
- H OREM LETTER TO JS KING 23 FEBRUARY 1966
  - DIFFERENCES OF OPINION REMAIN
  - WITHDRAW REQUEST FOR OVERRUN
  - FINAL REPORT TO BE FORWARDED SHORTLY

FIGURE C-7 FINANCIAL DIFFERENCES RESOLVED

DATE
ILME